THE PENNSYLVANIA STATE UNIVERSITY
DEPARTMENT OF GEOCHEMISTRY AND MINERALOGY
UNIVERSITY PARK, PENNSYLVANIA

Study of Structural and Mineralogical Significance of Meteorite Impact Sites, Including Mineral Paragenesis, High Pressure Polymorphs, Microfractures and Quartz Lamellae.

Third Annual (Fifth Semi-annual) Report
(January 1965 - December 1965)

to

National Aeronautics and Space Administration
Washington 25, D.C.

Grant No. NSG-473

D. P. Gold

B. Robertson

F. K. Aitken

V. Vand

O. F. Tuttle

P. J. Wyllie

January 1966

TABLE OF CONTENTS

SUMMARY

Most circular structures may be classified morphologically as rimmed pits, basins, shallow depressions, domes, pitted domes, annular depressions about central domes, rim synclines about central domes, and structurally as concordant or discordant (superimposed) with respect to the enclosing rocks. Specimens have been collected from some of the discordant types, varying in size from 3000 feet to 50 miles in diameter. Mapping and sampling of at least one concordant feature (e.g. Mecatina Lake) is deemed necessary to round out this current study on craters.

Specimens (mostly oriented) from the following circular features are now available for study: Holleford, and Brent, Ontario; New Quebec, and Lac Couture, Quebec; Kofels, Austria; the Pretoria Salt Pan, and the central granite dome of Vredefort, South Africa. Some of the maps showing sample locations, which were presented in earlier reports, have been brought up to date and reissued in this report, together with triclinicity values and fabric diagrams of microstructures. Sample location maps of Vredefort, the Pretoria Salt Pan, and from the Rubirizi, Katwe, and Fort Portal crater fields in Western Uganda, and the Homo Bay area in Western Kenya, will be issued in a separate report. Most of the East African specimens as yet are not available for study. Samples from these collections will be made available to serious workers in this field.

Analysis of the mesoscopic structures around the New Quebec crater are complete. A comparison of the geology and attitude of primary penetrative structural elements (foliation and lineation),

and such secondary structures as subvertical and sheeting joints, and shear planes in rim rocks with those in the country rocks was presented in the Second Annual Report. A 'ripple' wave of decreasing amplitude from the rim outwards is inferred by comparing S-pole diagrams of the sheeting joints from concentric zones about the crater. The diagrams show an annular maximum (invoking the symmetry rule) on small circles of decreasing diameter, whose centers are offset from the vertical to the southeast, probably indicating a non-vertically directed 'explosion'. A structural interpretation of the pre-crater regional structure using rotated structural readings and the gneissosity trends mapped by Currie (1965) is a complicated pattern generated mainly by northerly trending folds and cross folds on an east-northeast axis. These are consistent with N25°E trending fold axis plunging steeply south-southeast indicated from fabric analyses (see Second Annual Report 2). Preliminary work on the triclinicity of the potash feldspars reveal no systematic variation with location about the crater. No coesite has been detected in any of these rocks.

The results of structural and petrological studies of the Lac Couture area are presented in Appendix II. The Lac Couture depression is a superimposed structure of different age from the underlying and surrounding almandine-amphibolite facies granitic and granodioritic gneisses, and is apparently underlain by a pod of brecciated country rock. The dominant structural features are broad concentric folds, trending 165° and plunging 50° southeast, with cross folding on an east-northeast axis. No elevated rim is discernible, but a fossil rim or rim syncline may exist between 1-2 miles from the lake edge. Subvertical joints are more chaotic in attitude in the precints of the crater than in the country rocks. Glacial erratics of polymict breccia are present only on the western side of the lake, and are classified as comminuted rock matrix breccias, and breccias of crypto- and/or micro-crystalline matrix. Though no coesite has been detected in any of these breccias, they are interpreted as being of the impact variety because of deformation lamellae in quartz and feldspar. The angle between the c axis of the host quartz grain and the perpendicular to the lamellae range from 0 - 90°, with a maximum (20 to 25° class) coinciding with ω $(10\bar{1}3)$, and minor peaks coinciding with the r, z, s, and x cleavage planes. In grains containing two or more sets the majority of interplanar angles lie in the 35 - 40° class, which correlates well to 39° for those between companion faces of the ω cleavage. Similar planes are inclined at about 30° to the twin composition plane (010) in clastic plagioclase grains. Two sets intersect at about 60° in alternate twin lamellae. The degree of undulose extinction was found to be greater in the country rocks than in the breccias. Though no variation in the triclinicity of the K-feldspar between the breccias and the country rock was detected, some disordered grains were found ($2V{\cdot}32$-38°) in the breccias.

During the 'fall', while on a field trip to the Brent Crater (organized by the Dominion Observatory), additional specimens were collected. Orientation of planes of fluid inclusions coincide broadly to radial and concentric planes about the crater. No systematic variation was detected for triclinicity of the potash feldspars about the crater.

No coesite nor stishovite has been detected in any of the rocks, representing high stress environments, that have been treated.

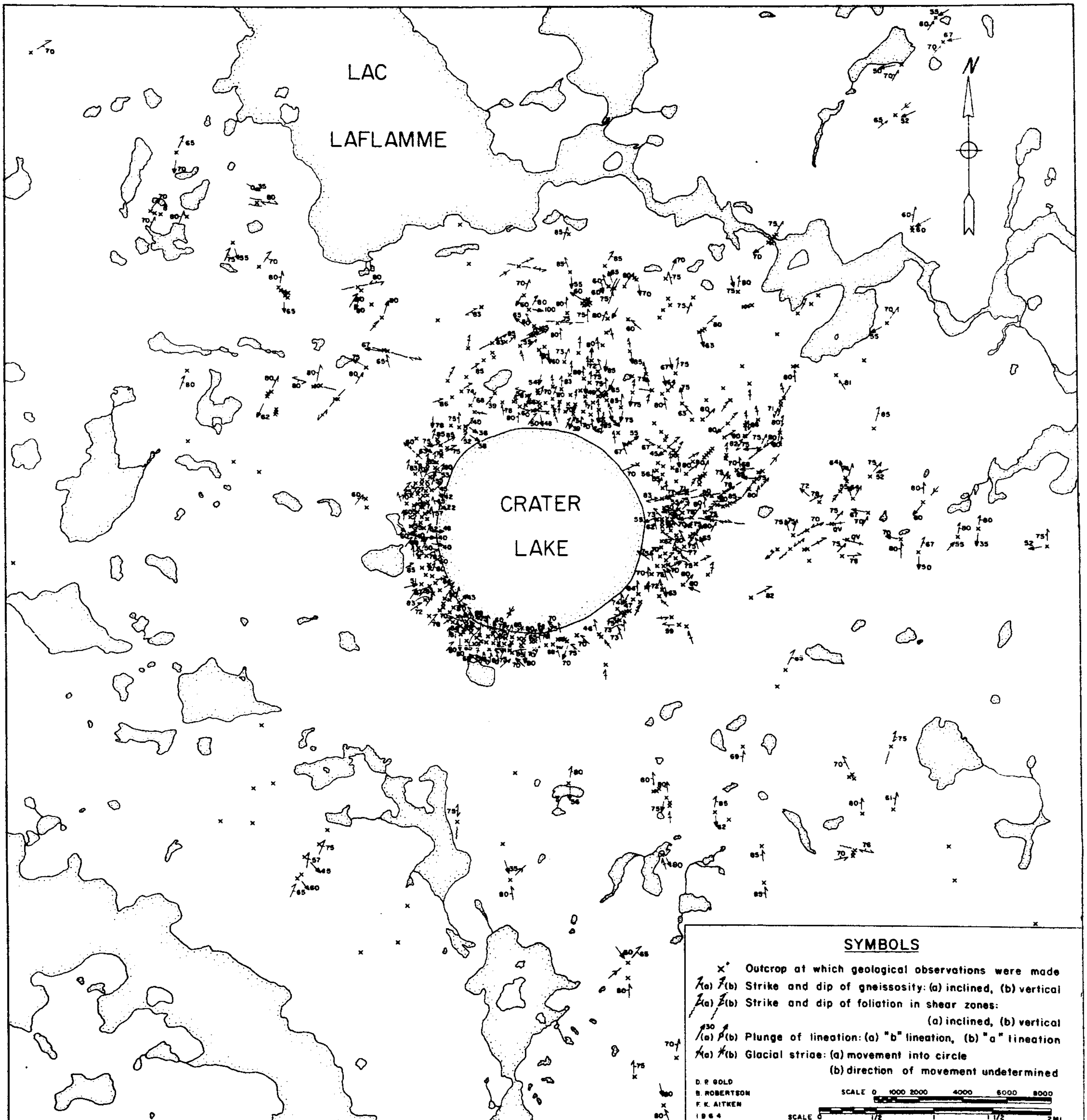
PERSONNEL

During the last quarter of the year Professor O. F. Tuttle left the campus to take up duties at Stanford University, California. His continued participation is valued, especially in the detailed mineralogy of the feldspars. Professor P. J. Wyllie, who took an active interest in certain aspects of the project, moved during the summer to the University of Chicago. Dr. D. P. Gold has directed and coordinated the project as principal investigator, with Professors Vand and Dachille available for consultation. Mr. P. B. Robertson, a graduate assistant, graduated with an MS degree in September, and has left Penn State to take up a post (on crater investigation) with the Dominion Observatory in Ottawa, Canada. His dissertation on the "Petrography of the Bedrock and Breccia Erratics in the Region of Lac Couture, Quebec", is to be published by the Dominion Observatory. Mr. F. K. Aitken, a graduate assistant, has been working on the staining, separation, and x-ray determination of the structural state of the potash feldspars around the craters. Mr. J. Gerencher, a graduate student, has shown an interest in craters, and hopefully will join the project in the New Year.

A STUDY OF MESOSCOPIC STRUCTURES AROUND THE NEW QUEBEC CRATER

In the Second Annual Report orientation diagrams were presented of the penetrative lineations and foliation, sheeting joints, subvertical joints, and nonpenetrative shears and lineations. The attitudes of these structural elements were compared for those rocks lying within the topographic rim with those of the country rocks. The penetrative structural elements were seen to have a more random orientation in the rim zone than in the country rocks. Also, additional sets of subvertical joints were developed in the rim rocks. Sheeting joints are ubiquitous. In the country rocks the sheeting joints have a subhorizontal attitude, whereas in the rim zone they have an outward dipping pattern as in a dome, with steep dips in the rim becoming progressively shallower outwards. A relationship between sheeting joint dip and degree of disorientation of the penetrative structural elements was demonstrated, proving that the sheeting joints of the rim rocks were developed prior to the formation of the crater. The main shear zones appear to have formed prior to rim uplift.

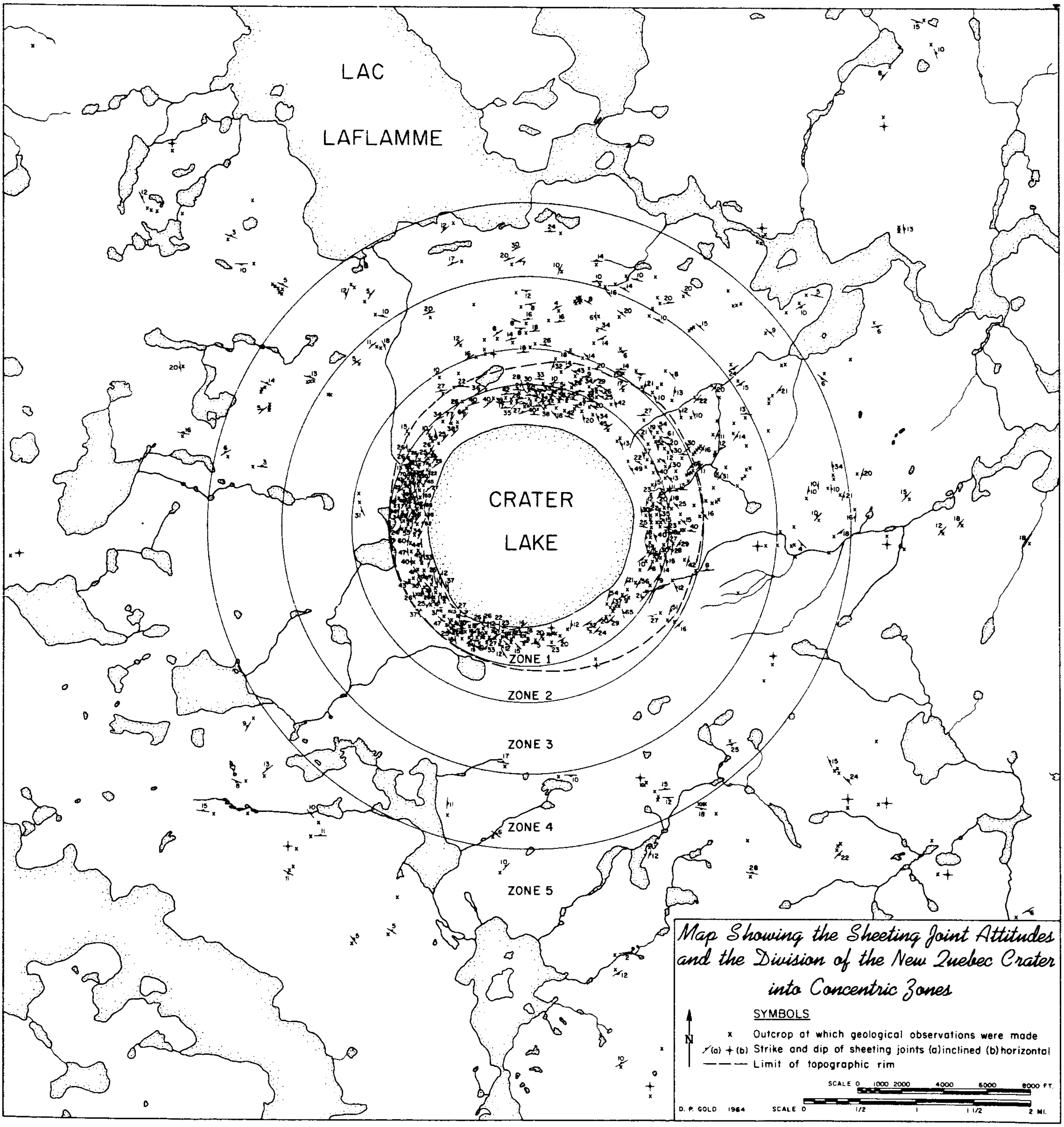
The positional structural data is shown on the map on page 6. The uneven sampling of data is indicated by the density of stations at which geologic observations were made, and reflects only the availability of bedrock exposure. Bedrock is well exposed in outwash scours and channels in the northeast quadrant, presumably because melt water from ice centered on the crater, developed better drainage patterns in the northeasterly direction. This also coincides with the prevailing direction of ice retreat as shown from glacial striae and eskers.



Map Showing the Main Structural Elements in the Area Around the New Quebec Crater

Damped shock waves may be preserved around craters as rim folds defined by, (a) folded attitude of beds in stratigraphic units, (b) concentric topographic furrows and ridges and an annular drainage pattern, (c) folded attitude of pre-existing s-planes (especially the mechanically induced planes), and (d) linear or planar features induced by the passage of the wave. At New Quebec the first condition is not met; the fourth has yet to be demonstrated. The topographic surface has been modified by glacial erosion and deposition, as well as subsequent mass wasting (solifluction), which tends to produce a stepped or ripple topography around domes under arctic conditions. Because the bedrock contours are not defined, the origin of the 2nd, 3rd and subsequent order rims could be many and varied. Inasmuch as the sheeting joints are the only convenient structural discontinuity (marker horizon) capable of reflecting degree of translational or rotational deformation, it follows that they would be the best fabric indicators of any damped shock wave radiating from the crater. Any fossil wave should show up in a statistical sense as rim folds of decreasing amplitude.

The location and attitude of these planes are shown as a sheeting joint map on page 8. Because of the poor distribution of sampling points, no rim folds can be displayed convincingly on the positional map, though in many cases reversals in dip directions were noted over short distances. A statistical approach, using orientation plots of sheeting joint attitudes from successive annular zones about the crater, are summarized on page 9. The orientation diagrams for the successive zones,



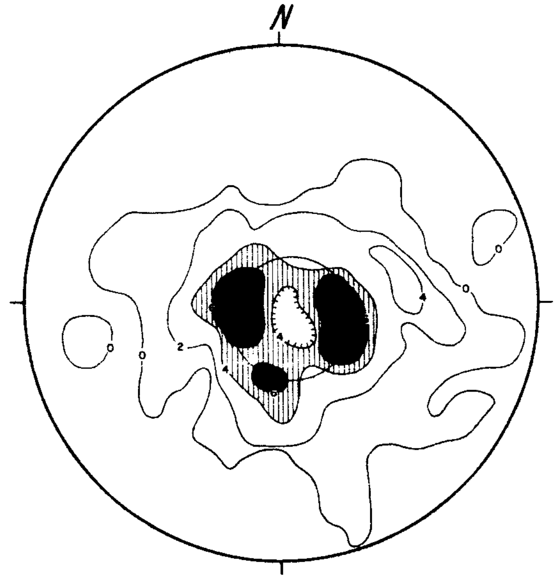
Map Showing the Sheeting Joint Attitudes and the Division of the New Quebec Crater into Concentric Zones

SYMBOLS

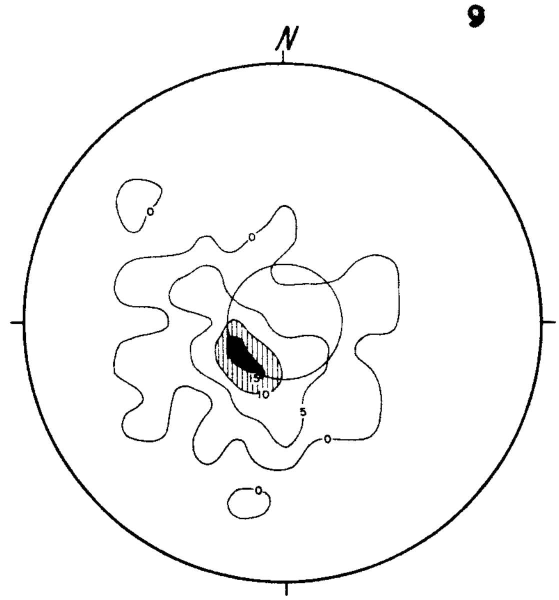
x Outcrop at which geological observations were made

(a) (b) Strike and dip of sheeting joints (a) inclined (b) horizontal

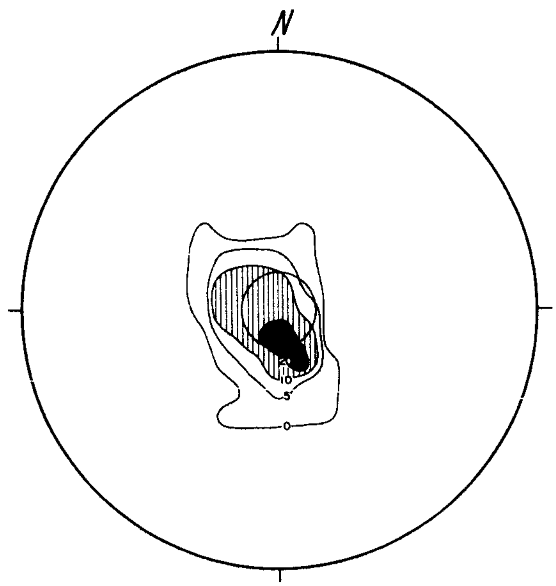
—— Limit of topographic rim



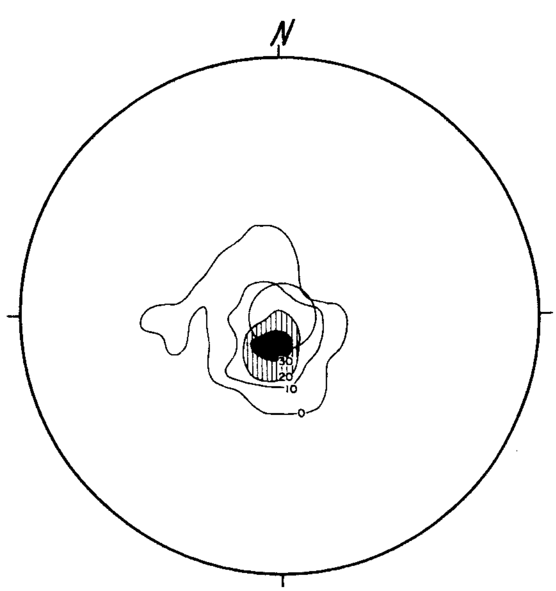
1. Contours 0-2-4-6 % per 1 % area (56 points)



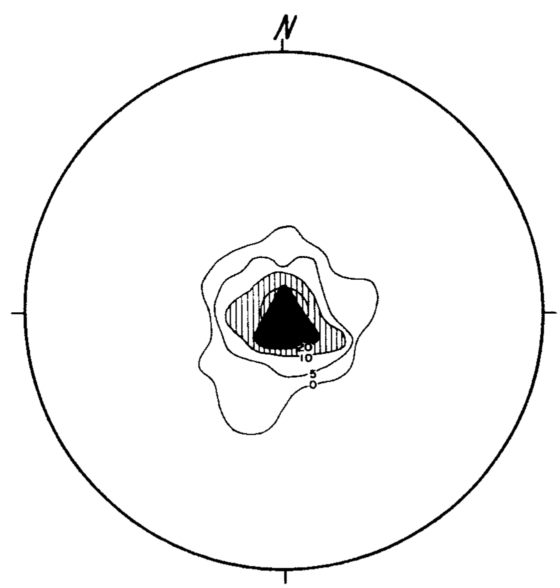
2. Contours 0-5-10-15 % per 1 % area (52 points)



3. Contours 0-5-10-20 % per 1% area (43 points)



4. Contours 0-10-20-30 % per 1 % area (39 points)



5. Contours 0-5-10-20 % per 1 % area (44 points)

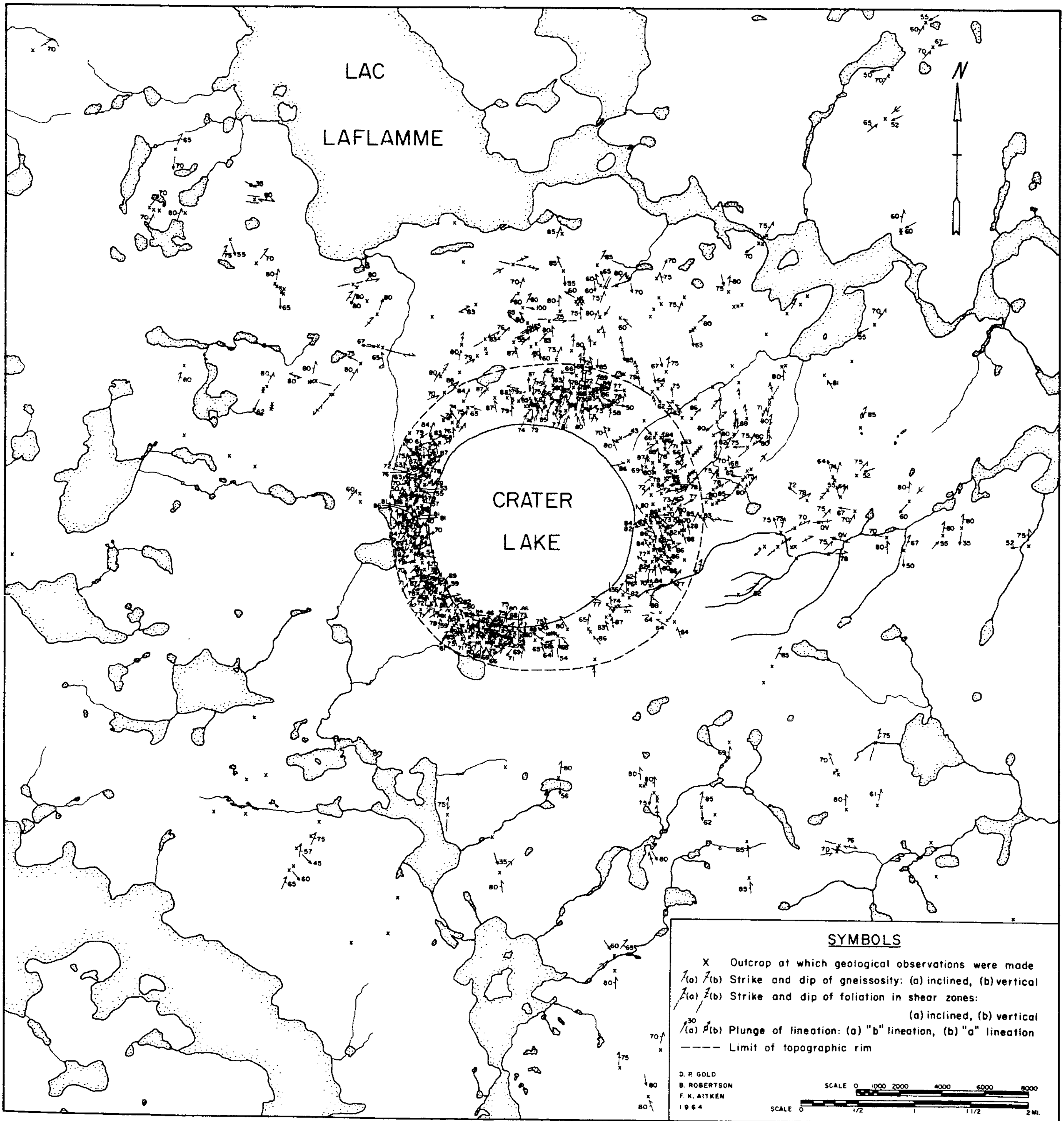
1 to 5, are shown as contoured S-pole diagrams correspondingly labelled 1 to 5. The limits of the arbitrarily chosen concentric zones are shown on page 8. Selection of the most meaningful zone boundaries is facilitated by inspection of a map on which sheeting joints are recorded.

It should be noted that only in zone 1 is the sampling data sufficiently well distributed to give rigorous results. The lack of even sample distribution is apparent as a distinct bias in the diagrams representing zones 2, 3, 4 and 5. By invoking the symmetry argument or symmetry rule of structural geology, deductions concerning the symmetry of unknown parts can be drawn from the knowledge of the symmetry of interrelated parts. Thus by assuming the symmetry properties of zone 1 (good sample distribution) would prevail in the other zones (for which the data has a strong geographic bias), then the fabric diagrams of the latter could be completed to conform in symmetry with the former. This entails inserting a nearly vertical axial symmetry axis and generating an annular symmetry maxima about it, similar to that depicted in diagram 1, page 9. However, as only the observed data are plotted, a small circle is drawn symmetrically through the maximum, which should define the annular maxima in the symmetrically complete diagrams.

The apical angle of these small circles decrease from 39° in zone 1, 37° in zone 2, to 25° in zone 3, 21° in zone 4, and 15° in zone 5. Whereas the centre of the small circle for zone 1 is inclined 84° in direction 146°, those for zones 2, 3, 4, and 5 are drawn in vertical in the diagrams on page 9. If the centers for the latter zones are taken as the same as for zone 1, then the apical angles of the small circles defining the annular maxima are reduced to 37°, 18°, 17° and 10° respectively. This is a more likely situation as the symmetry axis of sheeting joints in the country rocks (see contoured s-pole diagram in Second Annual Report) plunges steeply to the south. The 10° reading for zone 5 is taken to represent background. The tilt of this symmetry axis could represent, (a) some recent unusually active uplift of the Cape Smith-Wakeham Bay geosyncline belt to the north, or (b) a non vertically directed process of crater formation.

As the diameter of the annular maxima decreases so decreases the possibility of opposing dips, of marked angular difference, locally and on diametrically opposite sides of the crater. There is some ambiguity in interpretation of the diagrams as the annular pattern defines equally well (a) circular monoclinal structures (dome) of decreasing outward dip, or (b) concentric rim folds of decreasing amplitude. In zones 1 and 2, the former apparently prevails, though ripples may well be present on it. For zones 3 and 4 the pattern is interpreted as being due, at least in part, to rim folds. A statistical approach utilizing both orientation and positional data e.g. a Fourier smoothing function, should be tried as it is likely to yield the best results.

In the northeast sector where bedrock exposures are abundant, the fold pattern appears to be one of open folds with steep plunge. Variation of the plunge attitude has hampered elucidation of the fold type, but suggests that there has been more than one period of deformation to produce a complex pattern of cross folds.



"Pre-Crater" Structural Map of the Area Surrounding the New Quebec Crater
(Rim attitudes are rotated into a horizontal plane about the sheeting joint dip.)

Structural trends may be constructed by smoothing and extending foliation trends into continuous lines. The results agree fairly closely with the average trends of gneissosity drawn by Currie (1965, p. 151), except for the northern rim, where trends converge northwards rather than to the south. Closure of these trends produces an irregular pattern of similar open folds. Because the rim rocks have suffered both rotational and translational strain (uplifted position and tilted attitude), the regional structure can be seen correctly only if the gneissic trends are corrected to their pre-crater attitudes. This is accomplished by rotating the attitude of the rim rocks into the horizontal about the sheeting joint dip and projecting onto the present position (see Pre-crater structural map on page 12). A smoother trend pattern results.

Conclusions:

Interpretation of structural trend lines is facilitated by correcting the structural readings of the rim rocks to their pre-crater attitudes. The structural trend lines then define complex folds rather than north-south lines. The crater appears to be a local structure superimposed upon regional complexely folded rocks.

References:

Currie, K. L., 1965. The geology of the New Quebec Crater: Can. Jour. Earth Sci. Vol. 2, p. 141-160.

MICROFRACTURES IN QUARTZ FROM THE BRENT CRATER

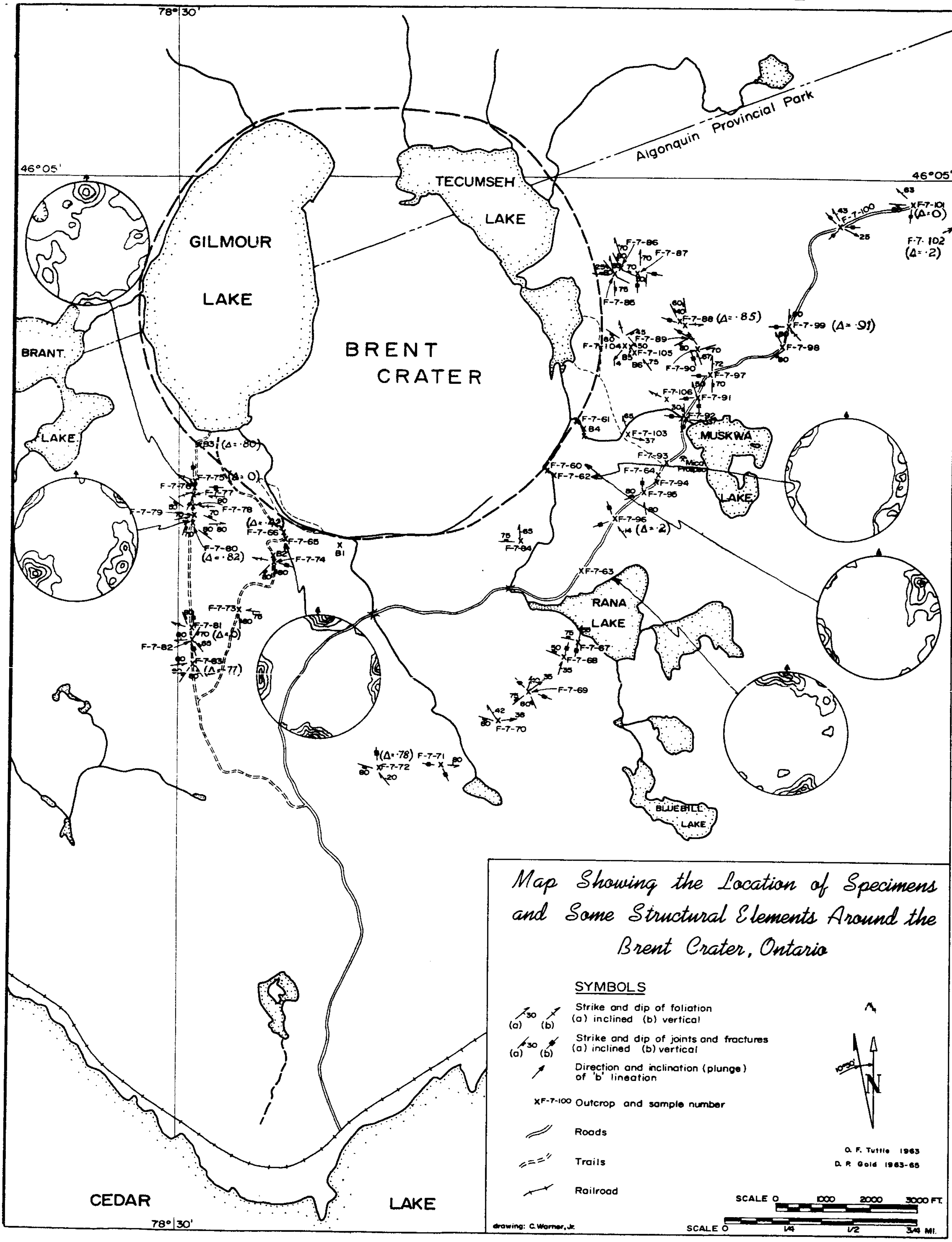
Orientation diagrams of the microstructures (fractures and planes of fluid inclusions) in quartz from rocks around the Brent Crater are summarized in the diagram on page 15. The maxima coincide approximately to planes radial and concentric to the crater. This geometric relationship requires further testing, as does the apparent relationship between microfractures to mesoscopic joint planes. Recently, measurements relating the orientation of the microfractures to the c axis of the host grain were made. In a plot of 200 $c \wedge \perp$ fracture plane measurements for specimen F7-80, maxima were found in the following classes: 10-15°, 35-40°, 50-55°, 80-85°, 85-90°, which may correspond to the cleavages ?, ω, ξ, r and z, x, m and a, respectively. For specimen F7-76 maxima fall in the classes 15-20°, 50-55°, 55-60°, 80-85°, 85-90°. It will be of interest to establish whether these fractures persist in the same relationship away from the crater.

Other deformation features being studied in quartz include the degree of undulose extinction, the orientation of extinction boundaries, and asterism (angular spread of optic axis) within single deformed grains. Subfabric diagrams of the c axes of quartz are plotted during the processing of the rest of the data.

References:

Bloss, F. D., 1957: Anisotropy of fracture in quartz: Amer. Jour. Sci., Vol. 255, p. 214-225.

Bloss, F. D., and Gibbs, G. V., 1963: Cleavage in Quartz: Amer. Min. Vol. 48, p. 821-838.



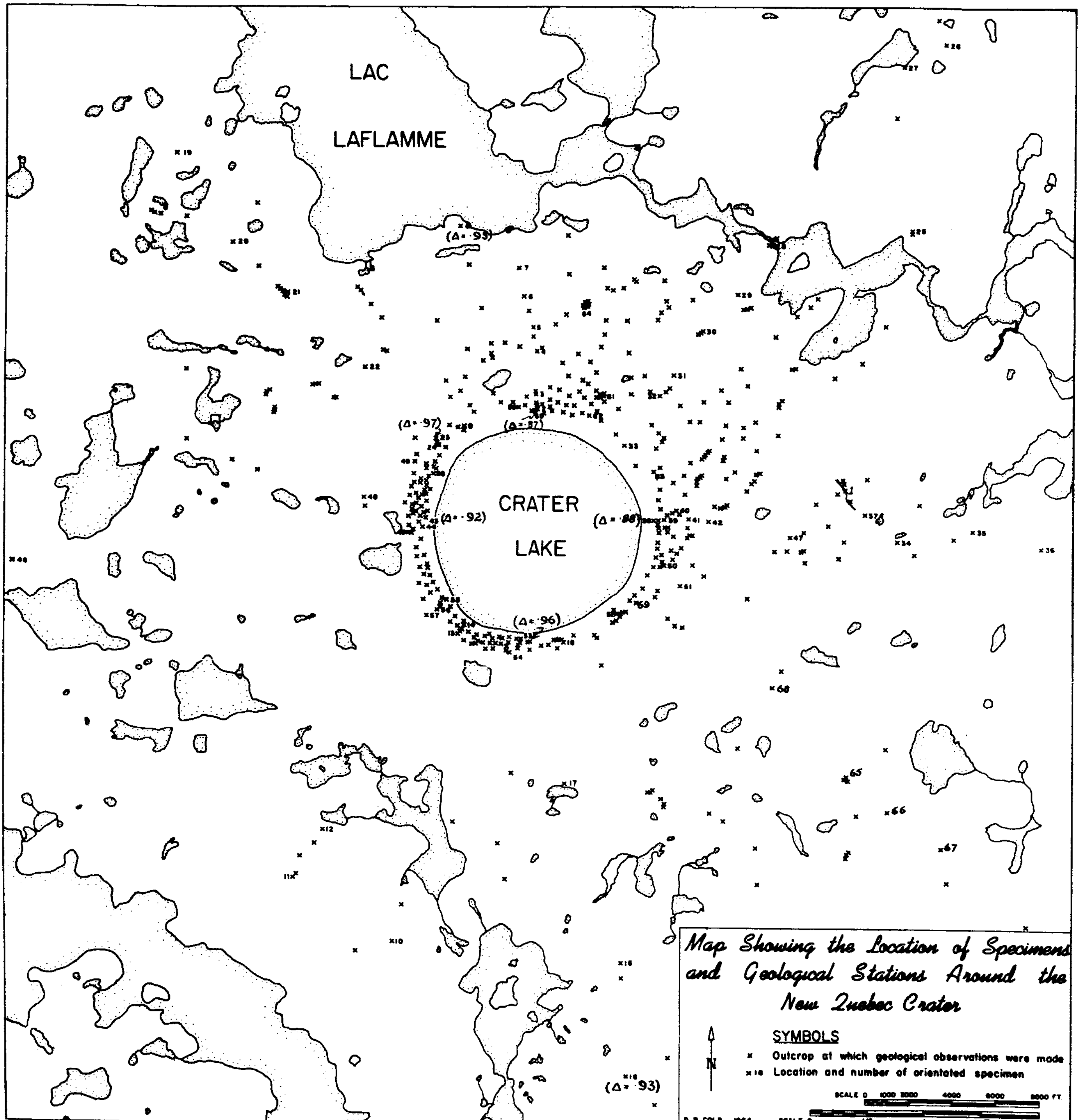
Map Showing the Location of Specimens and Some Structural Elements Around the Brent Crater, Ontario
SYMBOLS
Strike and dip of foliation (a) inclined (b) vertical
Strike and dip of joints and fractures (a) inclined (b) vertical
Direction and inclination (plunge) of 'b' lineation
XF-7-100 Outcrop and sample number
Roads
Trails
Railroad
O. F. Tuttle 1963
D. R. Gold 1963-65
SCALE 0 1000 2000 3000 FT.
SCALE 0 1/4 1/2 3/4 MI.
drawing: C. Warner, Jr.
78°30'
46°05'
GILMOUR
LAKE
TECUMSEH
LAKE
BRENT
CRATER
BRANT
LAKE
Algonquin Provincial Park
MUSKWA
LAKE
RANA
LAKE
BLUEBILL
LAKE
CEDAR
LAKE

REPORT ON THE STRUCTURAL STATES OF POTASH FELDSPAR FROM BRENT AND NEW QUEBEC CRATERS

The structural state of potash feldspar is related to the degree of Si-Al ordering in the tetrahedra, and varies with environment. The ordered form is maximum microcline (triclinic); the disordered form is orthoclase or sanidine (monoclinic). The degree of ordering may be expressed in terms of the departure from monoclinic symmetry. With slow cooling (most plutonic rocks) an ordered state is approached, whereas with rapid cooling (volcanic rocks) a disordered state (sanidine or glass) may be frozen in. In rocks that have been shocked and heated in an event such as a meteorite impact, disordered forms should be produced.

The structural state may be determined by measuring the 'triclinicity' from the separation of the 131 and $1\bar{3}1$ peaks on an x-ray diffraction pattern. This separation, expressed in difference of 'd' spacing, multiplied by a factor of 12.5 gives the triclinicity (Δ) value. For sanidine is Δ=0; for maximum microcline Δ=1. This may also be determined from the separation on the 130-$1\bar{3}0$ peaks or the 111 and $1\bar{1}1$ peaks.

The preparation and determination is straight-forward but tedious. About 10 grams of rock are crushed to a size range of from 1/4 to 1/2 mm, and 'cleaned' in a Franz isodynamic separator. The quartz and feldspar fraction is stained to distinguish potash feldspar, which is then hand-picked (approx 1 gm) under a stereo microscope. A standard is added, then the mixture is ground in acetone and water, and x-ray mounts prepared. The 2θ angles are read off the diffraction patterns and fed into a digital computer to obtain the triclinicity values.



Map Showing the Location of Specimens and Geological Stations Around the New Quebec Crater

The results to date are shown on pages 15 and 17. Values for the New Quebec crater rocks are all close to maximum microcline. At Brent the distribution is more complex. In three specimens the K-feldspar is monoclinic, and in another two there is but a slight separation of peaks to which an extrapolated value of 0.2 has been assigned. Yet another sample is intermediate, with a value of 0.42. The remainder are near maximum microcline. The pattern is puzzling and as yet, no explanation is offered. Additional measurements are being made on rocks from both these craters as well as for the other craters from which specimens are available.

References:

Chayes, F., 1952: Notes on the Staining of Potash Feldspar with Sodium Cobaltnitrate in Thin Section: Amer. Min. Vol. 37, p. 337-340.

Goldsmith, J. R., and Laves, F., 1954: The Microcline-Sanidine Stability Relations: Geochim. et Cosmochim. Acta, Vol. 5, p. 1-19.

____________________ 1954: Potassium Feldspars Structurally Intermediate between Microcline and Sanidine: Geochim. et Cosmochim. Acta, Vol. 6, p. 100-118.

MacKenzie, W. S., 1954: The Orthoclase-Microcline Inversion: Min. Mag. Vol. 30, p. 354-366.

SEARCH FOR COESITE AND STISHOVITE

The train designed to recover and detect coesite and/or stishovite in rocks from varied high stress geologic environments, has been reorganized to accommodate larger samples. Instead of the 10 gram samples of crushed rock which were taken previously, 100 gram samples are now being processed. The time required to reduce each sample to about ·1 gm is from 2 to 3 months. The samples currently being treated include mylonite from the New Quebec Crater, pseudotachylite, explosion breccias from the Montreal area, cleaved quartzite, and impact breccias from Lac Couture.

The search for coesite and stishovite continues, but, as yet, none has been detected except in the control sample (suiveite from the Ries Kessel).

PLANNING FOR THE NEXT SIX MONTH PERIOD

The proposed program emphasizes bringing to completion certain studies already in progress. These include:

a) mesoscopic structural studies around the other craters;

b) measurement of the triclinicity of the potash feldspars from all specimens collected which are suitable;

c) run all samples so far prepared for possible detection of coesite and stishovite;

d) microstructural analysis around the Brent Crater.

The long range studies which are in progress, and will be continued include:

a) microstructural analysis around the remaining craters;

b) petrographic description on the remaining craters;

c) thermoluminescence studies on rocks from the craters;

d) develop 2V trend diagrams for the feldspars around the craters.

Proposed additional studies:

a) The need for structural and petrological data on a concordant type crater is clear. I hope the necessary permission can be obtained to start a graduate student on a mapping and laboratory investigation on such a crater with a view to writing this up as an MS thesis.

b) The establishment of a calibration curve showing the effect of shock on the structural state of potash feldspar using controlled artificially shocked material.

PAPERS PUBLISHED, IN PRESS, OR IN PREPARATION

Jahns, R. H., McKague, L., Tuttle, O. F. Microjointing in basement; A discussion: Geol. Soc. Amer. (in press).

Gold, D. P., 1965. Circular structures on the Canadian Shield: Quart. News Bull. Geol. Soc. South Africa, Vol. 8, No. 3, p. 24-27. (See appendix I).

Gold, D. P., and Robertson, P. B., 1965. Structural studies on the New Quebec and Lac Couture Craters, New Quebec, Canada: Geol. Soc. Amer. Absts. Ann. Meeting, Kansas City, 1965, p. 63-64.

Robertson, P. B. 1965. Deformation lamellae from the Lac Couture Crater, Quebec: Geol. Soc. Amer. Absts. Ann. Meeting, Kansas City, 1965, p. 135.

Robertson, P. B., 1965. Petrography of the bedrock and breccia erratics in the region of Lac Couture, Quebec: MS thesis, The Pennsylvania State University, 112 p. (See appendix II).

Gold, D. P., Structural studies around the New Quebec Crater. Part 1. Mesoscopic structures. (In preparation).

APPENDIX I

CIRCULAR STRUCTURES ON THE CANADIAN SHIELD

With man's thoughts turned towards outer space and a possible lunar landing within the next half decade, there is a compelling need for definitive studies of the large circular structures on earth. This study is limited to circular features in 'granitic' terrains because petrographically homogeneous rocks provide a better control, and because unrecycled quartz (primary or recrystallized) is a prerequisite for the microfabric studies. The Precambrian shield of Canada was selected as the sampling area because of its large size (close to 1.8 million square miles) and long history of geologic stability (since early Palaeozoic) afforded an adequate sample in both space and time.

Most of these circular structures were spotted during systematic study of aerial photographs; some are large enough to show up on regional topographic maps, others are found only by geophysical means. These features may be classified morphologically as follows: those structures which possess

1. distinctive negative features, and include (a) rimmed pits, (b) rimless pits and/or steep basins, (c) broad shallow basins.
2. distinctive positive features, and include (a) ringed mountains and hills, some with central depressions, (b) domes, (c) annular depression with central dome, (d) annular depression with elevated central basin, (e) rim syncline around central dome (Vredefort type).
3. others, which include (a) large arcuate structures, and (b) circular geophysical anomalies without topographic expression.

A further distinction may be made between those structures which are clearly superimposed (discordant) upon the country rock fabric and those which essentially are concordant.

The statistics of selected examples (not all from gneissic terrains) are given in Table 1.

In some the affinity with alkaline rocks is marked, and they are clearly eroded plutons. Most of the remainder are cryptovolcanic structures, characterized by uniform magnetic fields and central gravity lows. They are underlain by breccias consisting of country rock fragments in a comminuted country rock and/or glassy matrix, from which in places coesite has been found. Where drilled the breccias are seen to grade outward from allochthonous highly deformed glassy matrix type to autochthonous types into shattered and finally fractured country rocks. No verticallity to these breccias is evident: rather they are pod shaped and have a thickness roughly one third the diameter of the structure. The type of studies currently being undertaken and some of the results are as follows: (a) Measurement of the attitude of planes of fluid inclusions, microfractures, and deformation lamellae in quartz. The preliminary results from Brent show one set of fluid inclusion planes concentric to and another

Table 1

Circular Structure	Form	Diameter in miles	Depth in ft.	Cover	Age	Diameter of uplift	Gravity	Super-imposed	Comments
New Quebec	1a	2 miles	1300	825' water	L.Ter - L.Pl.	-	low	yes	Well developed rim: glaciated.
Holleford	1a	1.46	900	825' seds.	L.Є - E.Ord.	-	low	yes	Drilled - coesite in breccia.
Merewether	1a	650 ft.	160	120' water	Post Pleis.	-	?	yes	In proglacial seds.
Brent	1b	1.86	1080	1000' seds.	L.PЄ - M.Ord.	-	low	yes	Drilled.
West Hawk	1b	2	970	365' water 600' seds.	L.PЄ - L. Tert.	-	low	yes	Drilled.
Deep Bay	1c	6.2	2310	1400' seds.	L.PЄ - M.Cret.	-	low	yes	Drilled.
Lac Couture	1c	{9 lake {6 crater	?	320' water	L.PЄ - L.Tert.	-	low	yes	Deformation lamellae in Breccia.
Clearwater East	1c	14.1	900	450' seds.	L.Tert.	-	low	yes	Drilled - glassy breccia.
Manicougan	2c	38	-	eroded	Ord. - L.Tert.	13.4	low	yes	Glassy breccia.
Clearwater West	2d	20	150	eroded	L.Tert.	5	annular low	yes	Drilled - glassy breccia.
Carswell	2e	20	-	eroded	P.Prot. - L.Tert.	6.2	annular low	yes	Shattercones present.
Lake St. John	1c	20x30	?	?	L.PЄ - E.Ord	?	?	?	Structural basin?
Hudson Bay Arc	3a	275	?	?	E.PЄ - Pre Prot.	?	?	yes	{Inward dipping Proterozoic {seds over 180° of arc.
Spanish anomaly	3b	6	?	?	?	?	?	?	{Magnetic anomaly with no {topographic expression.
Mecatina	1b	{3/4 lake {2-1/2crater	?	water	?	-	?	concordant in gneiss.	
St. Hilaire	2a	2-1/4	-	-	Early Cret.	-	high	yes	{Vertical pipes, horizontally dif- {ferentiated, in Palaeozoic seds.
Mt. Johnson	2a	1900x2300'	-	-	"	-	high	yes	{ "
Mt. Yamaska	2a	2-1/4	-	-	"	-	high	yes	{Elevated hornfels collar around {eroded plug, in Palaeozoic seds.
Oka South	2b	1-1/4	-	-	"	-	high	yes	Ring-dyke dome.
Oka North	1a	1-1/2x3	600	250' seds.	"	-	high	yes	{Cone-sheet and ring-dyke {carbonatite.

radial to the crater. Deformation lamellae in Lac Couture breccia are shown to coincide with rational cleavage directions. (b) Fabric analysis of the following structural elements, lineation, foliation, subvertical joints, and sheeting joints help determine the extent of both flexural and fracture deformation. At New Quebec the sheeting joints are shown to be pre-crater, and can be used as a control plane. (c) The extent of solid state deformation around the crater has been investigated from thermoluminescent studies (following the stress induced glow curve peaks), and by measuring the triclinicity of the potash feldspar (degree of ordering between orthoclase (monoclinic, disordered) and microcline (triclinic, ordered). (d) The presence of alkali feldspar with low 2V and feldspar glass in low temperature environments may be the result of shock induced disorder. (c) Rocks from environments of high stress concentration (mylonites, friction breccias, diatreme breccias, cleaved quartzites etc.) are being tested for possible coesite. None has been found to date. Until more quartz-bearing rocks from a variety of geologic environments are tested systematically for coesite its usefulness as an 'impact' indicator is weakened. Its presence indicates extremely high pressures (18 kilobars, - or 40 miles deep) but does not necessarily prove an impact origin.

The shatter cones, which are found accompanying some of these circular structures, are perplexing, but appear to be intimately tied up with crater mechanics. Until shatter cone mechanism is underatood the criteria for which they stand will not be realized. They appear to be tensional rather than shear features, and commonly have an inhomogeneity at the apex (probably causing local stress concentration). The Geology Department at Wits, with its affiliation to mining, rock mechanics, civil engineering, and its close proximity to Vredefort, should consider a research program into shatter coning.

The three main hypotheses which have been advanced for the origin of these structures are:

1. Eroded volcanic vents and craters
2. Meteorite impact craters
3. Collapsed bubble domes.

None of these completely satisfies all the requirements, but the meteorite impact origin stands up best.

It is noteworthy that the central dome type craters (forms 2c, 2d, 2e) have diameters greater than 15 miles. In these the centers are uplifted after the development of the main crater form. Assuming an impact origin this uplift could be caused by the returning shock wave (in tension) reflected off the Moho or Conrad discontinuities. The development of a central uplift would be conditioned by the size of the crater and the thickness of the crust.

D. P. Gold
Dept. of Geochemistry & Mineralogy
The Pennsylvania State University
University Park, Pa. 16801
U.S.A.

APPENDIX II

The Pennsylvania State University

The Graduate School

Department of Geochemistry and Mineralogy

Petrography of the Bedrock and Breccia

Erratics in the Region of Lac Couture, Quebec

A thesis in

Mineralogy and Petrology

by

P. Blyth Robertson

Submitted in partial fulfillment
of the requirements
for the degree of

Master of Science

August 1965

Approved:

Associate Professor of Petrology,
Thesis Adviser

Head of the Department of
Geochemistry and Mineralogy

ACKNOWLEDGEMENTS

My sincere thanks are extended to D. P. Gold for his advice and assistance throughout the project. C. P. Thornton critically reviewed the manuscript and aided in the interpretation of several thin section features. The field work and laboratory studies were financed by The National Aeronautics and Space Administration, grant NSG-473.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont.)

LIST OF FIGURES

CHAPTER I

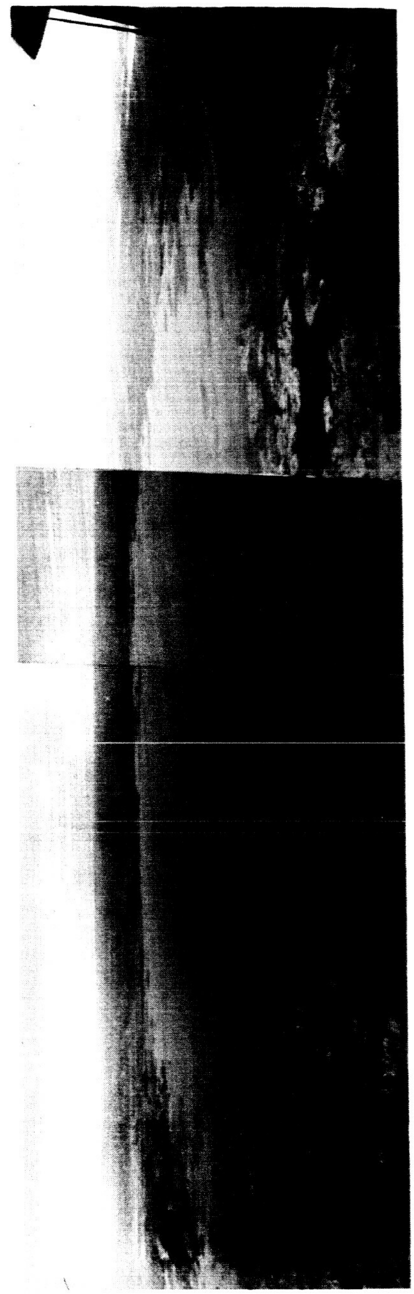
INTRODUCTION

Location and Topography

Lac Couture is a roughly circular lake situated in the northern part of the Province of Quebec, Canada, at longitude 75°20' and latitude 60°08' (Beals, Innes, and Rottenburg, 1960a) (see Figure 2). The lake is approximately ten miles in diameter with an inlet from the north, and it empties to the southwest. A series of islands lie around the perimeter at a distance of nearly four miles from the center. According to the Eskimo inhabitants of the village of Povungnituk (Povungnetuk), seventy miles to the west, on the eastern coast of Hudson Bay, the lake's Eskimo name, Tuktuek, means "place of many deer" (Gold, personal communication). This is in reference to the vast herds of barren-ground caribou, or "tuktu" (Banfield, 1964), which once roamed this area, but which are now substantially reduced in numbers.

This region of Quebec, sometimes referred to as New Quebec, lies north of the tree line and is thus classified as part of the true Arctic, according to one definition of the term (Lloyd, 1964). Low hummocks and ridges of outcrop are separated by shallow valleys of felsenmeer and caribou moss. In the immediate vicinity of Lac Couture the terrain has an average elevation of five hundred feet above sea level. This increases by one hundred and fifty feet about four miles to the west, and by several hundred feet to the highland, inland to the east and northeast (National Topographic Series, 1958a and 1958b).

Figure 1. Aerial view of Lac Couture from the southeast. Approximate scale through horizontal center of photograph 1 inch = 1.2 miles. (Courtesy of C. S. Beals of the Dominion Observatory, Canada).



The area is dotted with a large number of glacial lakes, and the highland to the east of Lac Couture forms the divide between those flowing east to Ungava Bay and those emptying into Hudson Bay. Lac Couture drains from its southwest corner via an unnamed river into Hudson Bay.

Statement of the Problem

It has been suggested that the basin occupied by Lac Couture has been created by the impact of a meteorite (Beals, Dence, and Cohen, 1964). The purpose of this study is to obtain evidence in support of this hypothesis or to suggest some other mode of formation for this crater. This objective was approached from three directions:

1. The mineralogy, petrology, and texture of rocks from the immediate vicinity of the crater were compared to those of the country rocks for possible variations.

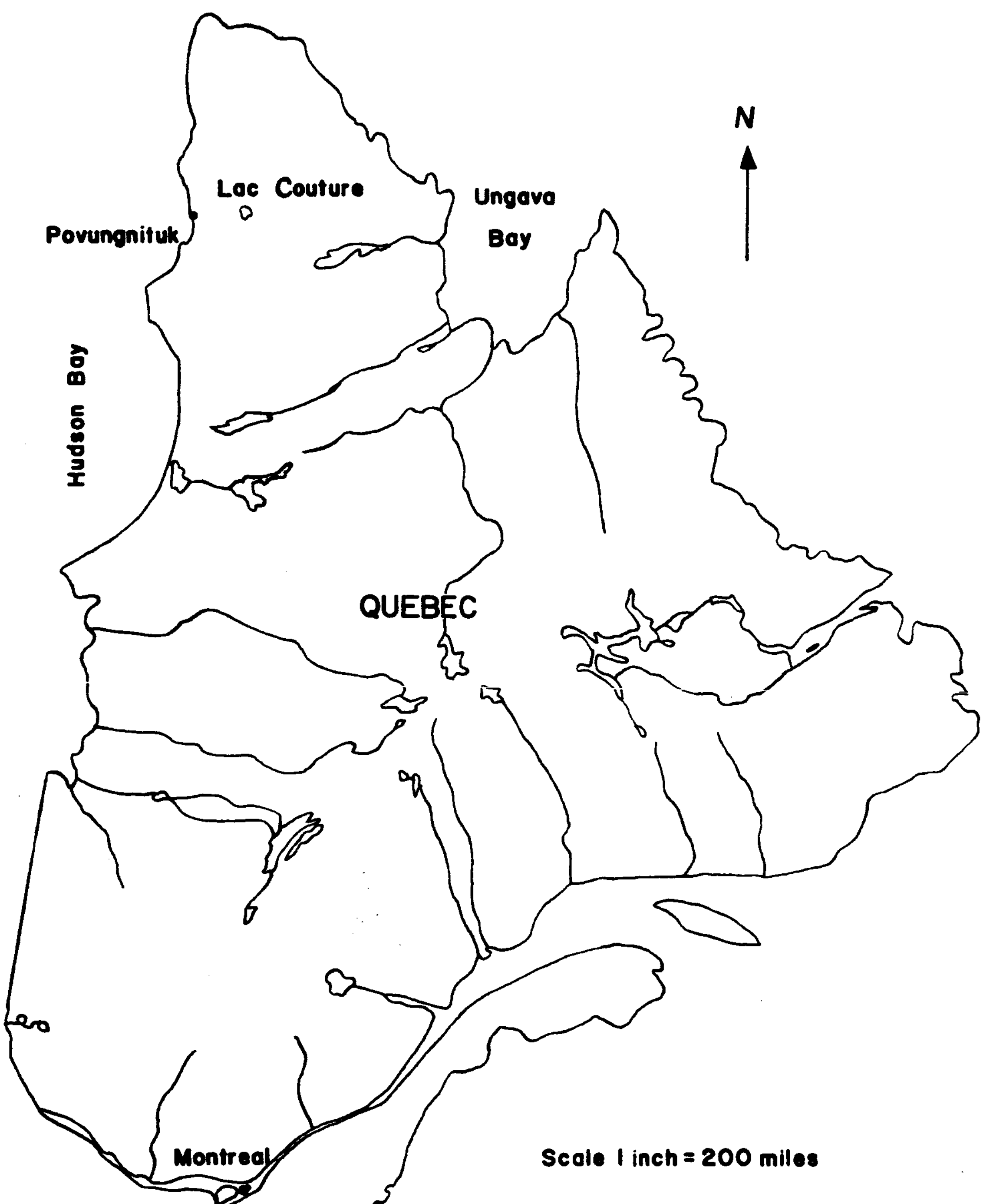
2. Structural elements of a regional scale were analyzed in the hope of detecting a systematic variation outward from the center of Lac Couture.

3. Samples were examined by X-ray methods to ascertain whether or not any high pressure minerals are present.

History of the Problem

The circularity of Lac Couture was noticed from aerial photographs by Dr. C. S. Beals of the Dominion Observatory of Canada in 1959 (Beals, personal communication), and he suggested that it might possibly be a fossil meteorite crater (Beals, Innes, and Rottenburg, 1960a and 1960b).

Figure 2. Sketch map of the Province of Quebec, Canada, showing location of Lac Couture.


N
Lac Couture
Ungava
Bay
Povungnituk
Hudson Bay
QUEBEC
Montreal
Scale 1 inch = 200 miles

Gravity measurements were carried out during the summers of 1959 and 1960 by the Dominion Observatory (Tanner and McConnell, 1964) in the area of New Quebec including Lac Couture, Concurrently geological observations of a reconnaissance nature were made by the Geological Survey of Canada (Kretz, 1960) over the same territory. Neither investigation, however, was designed to sample or map the Lac Couture area in sufficient detail to provide any clues to the origin of this circular feature. A party from the Dominion Observatory spent less than a week at Lac Couture during August, 1963, primarily visiting the islands within the perimeter of the lake. No mapping was undertaken at this time, but boulders of "... rock breccia of the type normally associated with meteorite impact." (Beals, Dence, and Cohen, 1964) were discovered on several of the western islands.

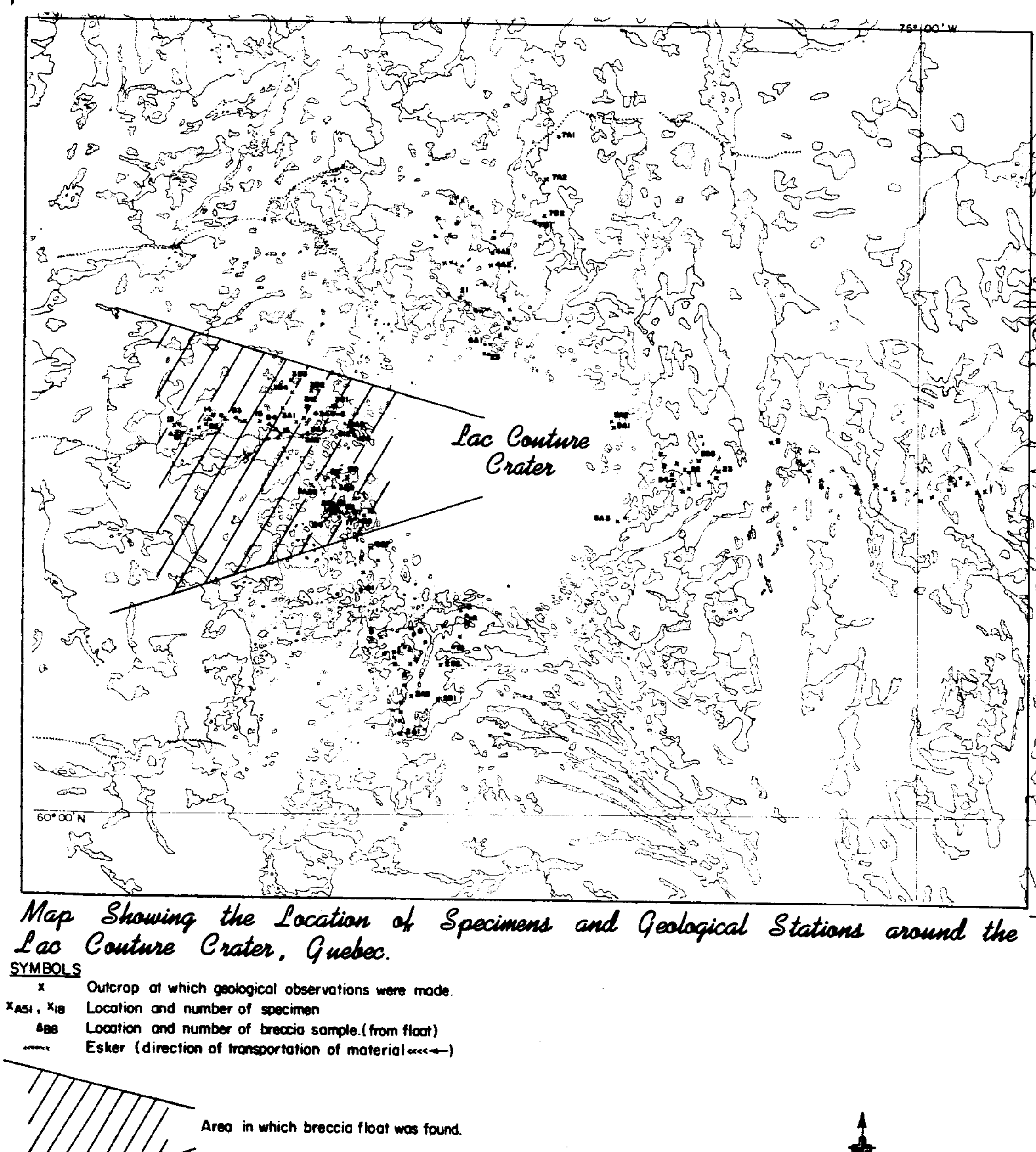
In the latter part of July, 1964, D. P. Gold, F. K. Aitken, and the author visited Lac Couture as a geological mapping party, sponsored by the National Aeronautics and Space Administration and conducted through The Pennsylvania State University. Ten days were spent in the area gathering data from which this investigation evolved.

Mapping and Sampling Procedures

Lac Couture was reached in a series of three aerial hops from Montreal, Quebec, the last stage being made from Povungnituk, in a single-engined float-plane. Ice conditions necessitated the establishment of a camp on the northeastern shore of the inlet to the lake, a distance of seven miles north of the center of Lac Couture. Difficult walking conditions created by the innumerable lakes, spongy caribou moss, and jagged felsenmeer, coupled with the large size of the lake and the inaccessibility of the islands, made use of the aircraft a necessity.

Four main radial traverses completed the primary mapping objective. These traverses extended from the center of the lake for distances of thirteen miles to the east, eight miles to the south, nine miles to the west, and nine miles to the north. Subsequent mapping consisted primarily of visiting as many islands as possible and of making short mainland traverses to fill in gaps in the four radial traverses. Geological observations were recorded at outcrop intervals of roughly a quarter of a mile, or where a significant change in rock-type occurred. Orientated hand specimens, marked in the field with a north arrow and the trace of the horizontal plane, were collected at approximately one mile intervals (see Figure 3).

Figure 3. Location of specimens and geological stations around the Lac Couture Crater (after D. P. Gold).



Map Showing the Location of Specimens and Geological Stations around the Lac Couture Crater, Quebec.

SYMBOLS

x Outcrop at which geological observations were made.

x A51 , x 18 Location and number of specimen

Δ 88 Location and number of breccia sample.(from float)

Esker (direction of transportation of material ←)

Area in which breccia float was found.

Lake

Scale 0 1 2 3 4 5 Miles

D. P. Gold , 1964

CHAPTER II

GENERAL GEOLOGY

Geological Setting and History of Geological Investigations

Lac Couture is situated on the Canadian Precambrian Shield in the northern extremity of the part of the Superior Province, which extends along the eastern shores of Hudson Bay. The Superior Province is a structural subdivision with geographic boundaries; it contains rocks of several geologic ages (Stockwell, 1964). The majority of ages determined in the New Quebec region correlate with the Kenoran orogeny (2,400-2,600 million years) of the Archaean eon. The two specimens located nearest to Lac Couture (seventy, and one hundred and twenty miles distant), whose ages have been determined, yield values which lie within the Aphebian era (1,640-2,400 million years) of the Proterozoic eon (Stockwell, ibid.).

Much of the interior of northern New Quebec has not yet been mapped geologically, except on a reconnaissance scale. The earliest geologists to visit this region restricted themselves to the coastlines of Hudson Bay, Ungava Bay, and Hudson Strait. Bell (1879) sailed along the eastern shores of Hudson Bay, making geological observations wherever he put in to shore. Low (1898) travelled thirty-five miles up the Payne River in 1897, and three miles up the Povungnituk River the following year (Low, 1900), in addition to exploring the coastlines of Hudson Bay and Ungava Bay. He noted very ancient, Archaean rocks which had been penetrated by granite bodies, transforming them into schists and gneisses near the mouth of the Povungnituk River.

Aubert de la Rue (1948) journeyed up the Kogaluk River in the summer of 1948 and passed forty miles to the south of Lac Couture in order to reach the Payne River leading to Ungava Bay. He described an Archaean complex of gneisses and granite similar to those referred to by Low, plus migmatites and granitic masses containing amphibolite enclaves.

Kretz (1960) entered the New Quebec region in 1959 in company with the Dominion Observatory party conducting gravity measurements. His geological report concerns an area of approximately 45,000 square miles and is based mainly on 320 geological observations within the area, and examination of rock specimens from 50 localities which he did not visit. He designated the region covering most of the interior of New Quebec and surrounding Lac Couture as the Interior Plateau; it is the geology of this geographical division which is most applicable to this review. According to Kretz (ibid.), granitic rocks varying in composition from granite to granodiorite underlie a large part of the Interior Plateau. Quartz monzonite seems to be the most abundant of these rocks. Numerous inclusions of a more basic composition form layers, irregularly shaped lenses, and schlieren in the granitic rocks. A strong gneissosity (Rice and Harker, 1961) in the granitic rocks is rare, but a faint gneissic structure is equally as common as none at all. A large swarm of diabase dykes, trending northwest, was recorded by Kretz (ibid.) in the northeast part of the Interior Plateau.

His impressions of the geology in the immediate vicinity of Lac Couture were developed from a single field observation, and eight non-field examinations. The geological picture here conforms to the broad scheme with only minor variations. He distinguishes massive granitic rocks, and granitic rocks containing more basic inclusions.

Stevenson (1963, 1965) mapped the geology of parts of New Quebec in 1961 and 1963. In addition to the granitic gneisses and amphibolites, he mapped a narrow band of biotite-hornblende gneiss derived mainly from volcanic rocks, eight miles northwest of Lac Couture.

Geology of the Lac Couture Region

Observations made by the author, in the field and laboratory, on the geology of the Lac Couture region agree, for the main part, with previous descriptions. The area is underlain by granitic rocks which range in composition from granite to granodiorite. Plagioclase and potash feldspar exhibit a large variation in their relative proportions in these rocks, whereas quartz is fairly constant in its abundance. The amounts of biotite, the predominant ferromagnesian mineral, and hornblende are also quite variable, to the extent of being absent in some specimens. Epidote, muscovite, chlorite, apatite, zircon, sphene, and magnetite are present in minor amounts in virtually all samples examined.

The granitic rocks are medium grained, equigranular, and commonly allotriomorphic-granular. A well-developed gneissosity does exist in a few localities, but usually this banding is poor and discontinuous, or altogether missing. A marked foliation, created by the parallel orientation of the biotite grains, occurs in scattered outcrops, and in two places an augen structure was noted.

Mafic segregations occur commonly within the granitic rocks. These segregations can be grouped as amphibolites on the basis of their mineralogy. Amphibole, biotite, clinopyroxene, and chlorite are abundant in these segregations. Quartz and potash feldspar are less common, though plagioclase is present in the same proportion as in the granitic rocks. The common accessory minerals are also present, but epidote is significantly more abundant in certain segregations.

A pronounced gneissic banding, illustrated by alternating ferromagnesian-rich bands and quartzo-feldspathic bands, is a common feature of most of these segregations.

Several diabase dykes strike northwest and transect the granitic terrain (see Figure 7). The average width of these dykes is between 2 and 3 feet, but the largest is 250 feet across and can be walked out for over a mile. The plagioclase laths and clinopyroxene grains are in a subdiabasic texture. Ilmenite and amphiboles together with late-stage minerals, which include epidote, quartz, apatite, and clay minerals, complete the mineralogy. In a few places the dykes possess an _en echelon_ arrangement, and some bifurcate.

Breccia fragments in the form of boulders, some several feet in diameter (see Figure 4), and smaller pieces of float were noted in a number of localities all on the western side of Lac Couture (see Figure 3). The majority of these float fragments, especially the larger ones, lie on the islands, while the smaller pieces were found

Figure 4-1. Breccia erratic.

Figure 4-2. Breccia erratic.

on the beaches of the lake, on an esker, and inland on the western mainland. The breccia consists of rock fragments up to a foot in diameter and of quartz and feldspar grains imbedded in a siliceous matrix. The matrix is composed either of clastic grains or of cryptocrystalline and microcrystalline grains produced by probable devitrification of a glass.

Glacial History and Geology

Glacial features, such as eskers, drumlins, striae, moraines, glacial valleys, and kames, are present in northern New Quebec. Evidence gleaned from a study of these features indicated to Kretz (1960) that the most recent continental ice-sheet flowed northward, westward, and eastward from the interior of this area. A lack of glacial features forty miles east of Lac Couture strengthens his belief that this was the area of ice accumulation. Kretz (*ibid.*) infers the direction of ice movement around Lac Couture to have been within plus or minus thirty degrees of due west. He also states that the maximum distance that glacial debris has been transported is in the neighborhood of eight miles.

Evidence of glaciation in the Lac Couture vicinity, as noted by Gold, Aitken, and the author, concurs with Kretz' theory. At least five eskers trending east lie to the north, west, and south of the lake (see Figure 3). Glacial striae from three outcrops strike 270°, 065°, and 260°.

CHAPTER III

PETROGRAPHY

Thin sections of the granitic rocks, amphibolites, diabases, and breccia fragments were examined under the polarizing microscope. To facilitate identification of plagioclase, potassium feldspar, and quartz, half of each thin section was stained by conventional techniques (Chayes, 1952; Rosenblum, 1956; Laniz, Stevens, and Norman, 1964). A five-axis universal stage was also employed in studies of the deformation lamellae, and optic axial angle measurements.

Granitic Rocks

The following observations were compiled from a detailed study of ten thin sections, a less rigorous investigation of thirty-five additional thin sections, and the study of the corresponding hand specimens.

Granitic rocks underlie most of the countryside around Lac Couture. Their dark gray to light gray weathered surface, combined with a gray to black lichen growing on them, presents a mottled or splotchy appearance in the field. They are generally medium-grained, with grain size varying from less than 0.05 millimeters to 10 millimeters within each thin section, and averaging approximately 1.5 millimeters. Although the grain size is variable, very few grains lie at either extreme so that the rock is essentially equigranular. Except for the minerals that can be recognized as crystallizing or recrystallizing at a later stage than the rest, all grains are anhedral and highly intergrown, resulting in an allotriomorphic-granular texture.

Quartz and two feldspars comprise about 90 per cent by volume of the mineralogy of the granitic rocks (for detailed modal analyses, see Appendix A). The quartz content ranges from 21.3 per cent to 34.5 per cent, where modal analyses were made, and averages about 30 per cent. A large degree of variation in the size of the quartz grains is exhibited within thin sections. The estimated mean of 1mm. to 1.5mm. is flanked by grains ranging down to less than 0.1mm. on the one hand, and up to 10mm. on the other. The smaller grains occur as aggregates on the margins of the larger grains, or in poorly defined lenses or bands. The quartz grains are completely anhedral; their margins sutured and interlocking with adjacent grains. Circular or oval grains are common as inclusions within the feldspars. Undulatory extinction is exhibited, to some degree, by all quartz grains. In some cases this feature is expressed as distinct, parallel bands which become successively extinct from one side of the grain to the other, or from one or two sites within the grains to its margins. In other cases, the extinction appears as a vague shadow moving across the grain or as irregular patches showing differential extinction. The grains showing undulatory extinction most strongly are those whose c-axis is horizontal or nearly so; the extinction bands are approximately parallel to the c-axis. Irregular fractures are present in quartz grains from a number of specimens.

The potash feldspar is consistently microcline microperthite. Threads and stringers of an unidentified plagioclase are present in the microcline in varying amounts, although in some samples very little evidence for this perthitic texture is visible. The amount of microcline varies from 0.3 per cent to 42.5 per cent by volume in those samples where modal counts were made, with most specimens containing between 10 and 20 per cent. The size of the microcline grains has the same range as does that of quartz, though the estimated average size is slightly larger than that of the quartz in the same thin section. The grains are anhedral, but are not sutured or interlocking to the same degree as the quartz grains. Microcline grains commonly are included as irregular patches in plagioclase grains, in one example to such an extent that the grains appear to be antiperthites. Rounded grains of quartz and irregular grains of plagioclase are common inclusions within the microcline. The typical twin pattern of microcline is uninterrupted, except in a few cases where the twin lamellae are offset or terminated by fractures. Strain extinction patterns are weakly developed in these same grains. Universal stage measurements yield optic axial angle values ranging from 76.4° to $82.7^{\circ} \pm 1^{\circ}$ for $2V_{\alpha}$ of the microcline of the granitic rocks (see Appendix D).

Plagioclase feldspar is the most common mineral of the granitic rocks. The abundance of this feldspar ranges from 24.3 per cent to 64.3 per cent by volume; most specimens contain between 45 and 60 per cent. The plagioclase is an oligoclase whose composition varies from An_{14} to $An_{25\pm2}$ within the Lac Couture area. These composition values were obtained using the Rittmann zone method (Emmons, 1943) and Smith's chart (Deer, Howie, and Zussman, 1963) (see Appendix B). The anhedral grains have an average size between 1.8 and 1.5mm.; the total range is from less than 0.1mm. to 10mm. within a single thin section. Albite twinning is well developed and uninterrupted, although in a few samples the twin lamellae are bent in some grains.

Plagioclase grains also occur as irregular inclusions within microcline grains, and in turn, the larger plagioclase grains contain inclusions of quartz and microcline. In one sample, the large number of microcline patches within the plagioclase makes the mineral appear to be antiperthitic. The plagioclase is unzoned, except for the margins of most of the inclusions in potash feldspar. These inclusions are altered to a slight degree, but the margins show a narrow, unaltered rim, suggesting a less calcic composition. Twin lamellae are continuous from the interior through the rims of these grains. In at least one case, the rim only is twinned. Vermicular intergrowths of quartz within this rim, forming a myrmekite texture, range from absent or poorly developed to relatively abundant. The amount of myrmekite increases in other samples so that complete inclusions of plagioclase are now myrmekite, and a zone of myrmekite exists between every microcline-plagioclase boundary.

Biotite grains, or chloritized pseudomorphs after biotite, are present in the granitic rocks in amounts ranging, where modal analyses were made, from 0.5 per cent to 11 per cent by volume. Most specimens contain around 5 per cent or less of this mineral. Where the biotite is unaltered, its strong pleochroism is from X = pale yellow brown, to Y and Z = dark brown or dark greenish brown. The subhedral plates are of a more uniform size than the quartz and feldspar grains, and have an estimated mean length of one-half mm. The majority of biotite grains contain light green, ragged lamellae parallel to the cleavage traces, an indication of chlorite alteration. This alteration occurs in all stages from incipient to complete replacement with pseudomorphs after biotite. Muscovite, epidote, sphene, iron oxides, apatite, and zircon are present as granular or ragged intergrowths along the biotite cleavage traces. The latter two are surrounded in places by dark pleochroic halos within the host biotite grain. Sagenitic rutile is rarely developed in the biotite, and is best observed in basal sections.

Although a parallel alignment of the biotite plates is well developed in a few thin sections, in most it is poorly developed, or not observed. In hand specimen such alignment appears as a weak foliation.

Chlorite occurs intercalated along the biotite cleavage traces. Aggregates of shreddy chlorite grains commonly are present as a rim around magnetite grains. Pleochroism of the chlorite is moderate to strong, and ranges from X and Y = dull grayish green or blue green, to Z = colorless. Anomalous violet-blue interference colors aid in its identification.

Sphene, zircon, apatite, and iron oxides comprise the accessory mineralogy of the granitic rocks. They are usually present only in trace amounts, but can account for as much as 1.3 per cent of the mode. Apatite and zircon are found as euhedral to subhedral grains within, or closely associated with, biotite laths. Pleochroic halos surrounding the apatite and zircon are not abundant. Opaque, iron oxide minerals are present as anhedral or subhedral grains, or are segregated along biotite cleavage traces. Most of the grains are probably magnetite, but a small percentage, which are altered to a dull white in reflected light (leucoxene) and are closely associated with sphene, are thought to be ilmenite. Sphene is absent in most granitic rocks, but a few anhedral grains are found in close association with ilmenite, or aggregations of epidote, muscovite, and chlorite.

Muscovite and epidote occur in all the granitic rocks studied. Epidote ranges in volume from a trace amount to 1.3 per cent, in samples where modes were calculated, whereas the content of muscovite varies from a trace to 1.5 per cent in the same specimens. The subhedral or ragged muscovite laths are always found as sericitic alteration of plagioclase, and also along the margins and/or cleavage traces of biotite. Aggregates of several ragged laths of muscovite also are closely associated with segregations of accessory minerals and epidote. Vermicular intergrowths of a low birefringent mineral, assumed to be quartz, occur in some muscovite flakes.

Colorless to yellow, moderately pleochroic, epidote grains are found primarily as an alteration of plagioclase feldspar or as inclusions within biotite. Larger grains are present in aggregates associated with muscovite and accessory minerals, or as transgressive stringers and veins.

Bands of light and dark minerals, or a foliation, are not easily discernible, either in the hand specimens of the granitic rocks or in their corresponding thin sections. Biotite, chlorite, and muscovite laths in places exhibit a rude parallelism of their long directions, but in most samples this orientation is absent or undetectable. A tendency for biotite, muscovite, epidote, and the accessory minerals to occur together in narrow, discontinuous, parallel zones exists in almost half of these rocks. These bands alternate with quartz- and feldspar-rich zones, in which the quartz grains rarely are elongate parallel to the banding. A slight to, in places, distinct gneissosity is therefore developed in the granitic rocks.

The calculated and estimated modes of the granitic rocks indicate that the ratio of potash feldspar to plagioclase can range from almost zero to approximately two. This ratio, combined with the additional mineralogy, demonstrates a compositional range from granite to granodiorite. By far the majority of samples investigated tend to granodiorite. Because the composition of the rocks within this group, prior to the imposition of the gneissic structure is unknown, the typical "granitic" rock of the Lac Couture area will be called a granodiorite gneiss, rather than a gneissic granodiorite.

Inclusions and Variations in the Granitic Rocks

Several rock types occur as inclusions or segregations within the area underlain by the granitic rocks. These varieties are distinguished by major differences in chemical composition, of mineralogy, or by local differences in texture. A detailed thin section study was made of samples from eight outcrops, which represent the more common varieties. Seven of these specimens were selected primarily because of their difference in mineralogy from the surrounding granitic rocks, although, for the most part, they exhibit textural differences as well. The remaining sample was used to demonstrate only a local variation in texture. This last sample will be discussed first.

Approximately one mile inland from the eastern shore of Lac Couture, several outcrops of an augen gneiss were mapped. A similar, though less well developed texture was noted in two outcrops eight miles from the lake in the same direction. In the hand specimen (5D5), undulatory bands of light and dark minerals bend around augen of a pink feldspar. Investigation of the corresponding thin section revealed a gneissic texture, with grains ranging in size from less than 0.1mm. to 15mm. The largest grains are microcline microperthite and quartz "eyes". Undulatory extinction is strongly evident in quartz grains, both large and small. Plagioclase feldspar is present as smaller, anhedral grains, but not as augen. The plagioclase is an oligoclase of composition $An_{18 \pm 2}$, as determined by Smith's method (Deer, Howie, and Zussman, 1963). Subhedral biotite plates, pleochroic from pale yellow brown to dark brown, possess a good parallel alignment of their long directions, and form crude, parallel bands. A rare knot of anhedral biotite has developed within these zones. Vermicular intergrowths of quartz are present in these biotite flakes. Subhedral and anhedral grains of zircon, sphene, apatite, and magnetite occur together in aggregates or knots, within the biotite-rich bands. Epidote, muscovite, and bluish green hornblende are rarer constituents of these segregations. Alternating biotite-rich and quartz- and feldspar-rich bands bend around the larger augen of single microcline and quartz grains, or aggregates of these minerals.

The calculated mode (see Appendix A) reveals no significant variation between the mineralogy or composition of the augen gneiss and the granitic rocks.

The presence of pyroxene, and/or the increased abundance of amphibole, biotite, and chlorite, serve to distinguish several enclaves of mafic rocks within the granitic rocks. Samples B7, 2D5, 4A7, and 4D14 were examined in detail as examples of this feature.

Chlorite and epidote comprise an estimated 40 per cent of sample 2D5, with plagioclase accounting for the remaining 60 per cent. Sheaves of ragged grains, and clusters of smaller spherulites and semi-spherulites characterize the habit of the pale yellow to pale bluish green chlorite. Strong planar alignment of these laths create a marked foliation in the hand specimen. Subhedral and skeletal, weakly pleochroic epidote grains occur in aggregates closely associated with the chlorite. The two minerals occur together in poorly defined bands, which alternate with plagioclase-rich zones. The patchily and discontinuously twinned plagioclase was determined to be albite ($An_{1\pm2}$). Minor quartz, magnetite, and sphene complete the mineralogy of sample 2D5.

Examples of amphibolite inclusions are provided by samples B7, 4A7, and 4D14. All contain abundant amphibole and/or pyroxene, ranging in amounts from 32 per cent hornblende and 2.3 per cent pyroxene in B7, 69.3 per cent amphibole in sample 4A7, to 45 per cent hornblende, and 36.5 per cent pyroxene in sample 4D14. The amphibole is predominantly subhedral hornblende, with strong pleochroism X = pale yellow brown, Y = yellow green, and Z = blue green. A bleached hornblende, whose corresponding absorption colors are lighter shades than the host grain, is found as regular patches within the hornblende of sample 4A7. Basal sections of the host hornblende, in this sample, contain chlorite laths orientated parallel to the prismatic cleavage traces. Sections other than basal, and showing only a single cleavage trace, also exhibit chlorite alteration controlled by this cleavage. In these latter sections, laths of a lighter colored amphibole cut the cleavage obliquely. These laths are not separate mineral grains, but are simply variations within the hornblende. It appears that they form as compositional variations along fractures. The variation moves outward from the fracture and possesses a sharp rectangular outline. The refractive indices of the hornblende are greater than those of the bleached zone. The birefringence is also greater, but extinction and cleavage traces are continuous between the two varieties. As the development of this zone proceeds, chlorite forms in the central portion along the fracture. Epidote occupies this position where the zone has widened still further, and is in turn surrounded by chlorite, the bleached amphibole, and hornblende. Euhedral pyrite grains in places are found in the center of these concentric zones.

The subhedral pyroxene grains are colorless, or very pale green, and not visibly pleochroic. They are probably an augite as indicated by their estimated optic axial angles, which lie between sixty and sixty-five degrees, and their large extinction angle ($Z \wedge C = 40^{\circ}$).

Biotite is comparatively rare in the amphibolites, and commonly is present only as small laths in larger poikiloblastic hornblende grains. Plagioclase is a major constituent of sample B7 (42.3 per cent), but it is substantially reduced in amount in the other specimens. The composition of the plagioclase varies considerably in the amphibolites; from andesine ($An_{32\pm2}$) in sample 4D14, to oligoclase ($An_{23\pm2}$) in sample B7, to albite ($An_{9\pm2}$) in sample 4A7. Moderately pleochroic epidote comprises up to approximately five per cent of these rocks. The common accessory minerals are quartz, microcline, calcite, pyrite, ilmenite, sphene, and apatite which, in sample B7 comprise 14.4 per cent of the rock.

A gneissic banding is produced by alternation of parallel bands of quartz and feldspar minerals and bands of the dark minerals. This banding becomes a zonation in sample 4D14, where a narrow (one half inch) zone of pyroxene and andesine gives way to a hornblende zone, which in turn is succeeded by a strongly foliated biotite zone.

The remaining three samples, 4A4, 4D8, and 5D3 which show major differences from the granitic rocks, all possess a greater amount of epidote than the surrounding gneisses (see sample 2D5, Appendix A).

The epidote occurs as anhedral to subhedral grains, commonly in poorly defined bands with the ferromagnesian minerals or in stringers and veins up to several inches in width.

At outcrop 5D3 the strongly banded country rock has been transected by a granite pegmatite which shows no gneissosity. Glaciation has reduced the pegmatite to a skin approximately one half inch in thickness, coinciding with the sheeting joint surface of the gneiss. Both the pegmatite and gneiss are cut by numerous epidote veins possessing a common strike and dip. In thin section, the epidote is strongly pleochroic from yellow to colorless and occurs as stringers and patchy aggregates. The formation of the epidote is commonly controlled by the twin lamellae of the plagioclase grains. As derived from Smith's method (Deer, Howie, and Zussman, 1963), the plagioclase is a well twinned albite of $An_{1\pm2}$ composition. The twin lamellae of several grains are bent, fractured, or truncated. Patches of a low birefringent mineral, highly altered to a dusty brown granular mass, are incorporated within the plagioclase. The patches have crude rectangular outlines, cut across twin lamellae but are also terminated by the lamellae, have a lower refractive index than the plagioclase, and are selectively colored by the stain used to detect potash. The patches are probably orthoclase, creating an antiperthite relationship with the plagioclase.

The only other potash feldspar present in this specimen is included microcline grains within the epidote veins, and one or two larger, non-perthitic microcline grains. The latter are highly fractured, exhibit strong strain extinction patterns, and are cut by epidote veins. Other fractures are filled with comminuted, fine-grained quartz and microcline grains, highly stained by iron oxides. Another stringer of this comminuted material cuts through the section.

Anhedral quartz grains showing strong strain extinction and crenulated margins, anhedral sphene, and ragged grains of tremolitic amphibole are present in minor amounts. No definite banding can be detected in thin section but a weak gneissosity is evident in the hand specimen.

Specimens 4A4 and 4D8 are quite similar in that they are both albite-epidote-chlorite gneisses. The epidote content of the former was estimated at 50 per cent, whereas approximately 10 per cent is present in sample 4D8. Elongated aggregates of sutured quartz grains and poorly twinned albite ($An_{1\pm2}$ in 4A4, $An_{8\pm2}$ in 4D8) form sub-parallel, quartzo-feldspathic bands. Shreddy chlorite laths, muscovite, biotite, and sphene, in combination with epidote, form the alternate bands resulting in a gneissic structure.

Diabase Dykes

Two sets of diabase dykes transect the rock types already described. All the dykes mapped occur in the northern and eastern portions of the Lac Couture area. These black dykes range in thickness from less than 1 foot to 225 feet, and the largest one can be traced on aerial photographs for at least sixteen miles. The set to which the larger dykes belong strikes approximately 105°; the other set strikes approximately 135°. Thin sections from dykes of both sets and from the margins and interiors of the larger examples have been studied in detail.

No major differences can be distinguished between the petrography of the dykes of the two sets, and so a general description can be given for all specimens studied. Grain size of the holocrystalline matrix, at its sharp contacts with the country rock, averages between

0.4mm. and 0.6mm., with a few phenocrysts up to 1.5mm. The coarser-grained interior of the widest dyke has an average grain size of about 2mm., and contains coarse phenocrysts up to 7mm. in length. A sub-diabasic texture is created by the euhedral plagioclase feldspar laths and the subhedral to anhedral pyroxene and amphibole grains.

Well twinned, euhedral laths of plagioclase comprise between 37.5 per cent and 57.5 per cent by volume, in thin sections whose modes were calculated (see Appendix A). Determinations of composition, based on extinction angles of twin lamellae, indicate that the plagioclase near the contacts of the dykes is labradorite, ranging from $An_{62\pm2}$ to $An_{70\pm2}$. This becomes an andesine of composition $An_{36\pm2}$ near the center of the largest dyke, where it represents an estimated 50 per cent of the rock. Oscillatory zoning is common in generally untwinned plagioclase phenocrysts; it is absent in the laths which constitute the matrix.

Grains of colorless to slightly green clinopyroxene are generally anhedral to subhedral and occur interstitially to the plagioclase laths. Individual grains average approximately one-half mm. in length. These smaller grains also can form rounded aggregates up to 1.5mm. in diameter; these are not interstitial to the feldspar, but appear to be phenocrysts or pseudomorphs after phenocrysts. The commonly twinned pyroxene present in the narrow dykes and near the contacts of the larger dykes is probably an augitic clinopyroxene. Measured optic axial angles average between 47° and $49^{\circ}\pm2^{\circ}$ for $2V_{\gamma}$ in the five thin sections where values were measured. Strong alteration prevents similar measurements on samples taken from the interior of the larger dykes. The pyroxene in this case is also an optically positive monoclinic variety. Alteration of the pyroxene to chlorite and "uralite" is always present to some degree, especially in the coarser-grained samples. The unaltered and altered material accounts for between 31.8 and 53.3 per cent by volume of the mode, in samples which have been point-counted.

Amphibole occurs as hornblende and "uralite". The former is strongly pleochroic from X = pale yellow brown, Y = brownish green, to Z = bluish green or dark green. The corresponding absorption of the latter produces lighter shades of the same colors. The hornblende, present in subhedral individual grains or as a reaction rim on pyroxene grains, comprises from 3.3 to 11.0 per cent of samples whose mode was calculated. The uralitic amphibole is confined to the margins of the pyroxene and hornblende, where it forms as a late stage, ragged alteration. It is mixed with chlorite, from which it is distinguishable only by its higher birefringence. Orientations yielding a low birefringence make this distinction, at best, difficult. Point count data combines these two minerals, which make up between 6.3 and 19.5 per cent of the mode.

Subhedral laths of reddish brown biotite account for no more than 3.5 per cent of the mode, and usually are present only in trace amounts.

The only other minerals present in excess of one per cent are opaque minerals, epidote, and quartz. Subhedral, skeletal crystals of ilmenite, with a dull purplish alteration product (leucoxene) filling the voids, are the most common of the opaque minerals. Disseminated grains of pyrite and magnetite, plus the ilmenite, make up 2.3 to 6.5

per cent of the diabase samples whose modes were calculated. Weakly pleochroic epidote rarely is associated with interstitial quartz grains. One dyke, however, contains rounded aggregates of epidote grains, which appear to be pseudomorphs. In this sample epidote comprises 2 per cent of the mode. Anhedral, embayed quartz is present in the interstices of the plagioclase and pyroxene matrix, especially in the samples from the interior of the larger dykes. Several grains, separated by hornblende, are in optical continuity with each other. Euhedral needles of apatite are common inclusions within the quartz grains.

The subdiabasic texture in the diabases near their contacts gives way to a diabasic texture in the interior of the dykes. This latter is often obscured by the large amount of hydrothermal alteration products present in the coarser-grained samples.

Breccias

Numerous glacial erratics, found on the islands lying near the western shores of Lac Couture and distributed inland to the west in a narrow fan (see Figure 3), were observed to be breccias. The erratics of the islands are abundant and reach several feet in diameter (see Figure 4). Westward, the breccia boulders become less frequent and smaller, until at a distance of nine miles from the lake's center they occur only as pebbles, approximately two inches or less in diameter. Here they are found usually on gravel beaches or in the material forming an esker.

These rough, highly pitted, and sometimes crumbly erratics contain rock fragments up to one foot in diameter (see Figure 4) in a weathered matrix. The color of the matrix varies from white to gray, to dull purple or red, depending upon its chemical composition and texture. Although all colors are found in the matrix of the larger erratics, the small pebbles composed of breccia are almost always a rusty red.

Detailed study of thin sections from thirty-three breccia samples indicates that the nature of the matrix can serve to distinguish two main types of breccia: those whose matrix is made up essentially of finely comminuted material, and those in which cryptocrystalline or microcrystalline material forms the matrix.

Comminuted matrix breccias. Rock and mineral fragments span the complete size range from approximately 1 foot down to less than 0.1mm. In five of the thin sections studied, the interstices between the larger fragments appear to be completely filled by fine-grained, clastic material, and no evidence of a homogeneous cement or crystalline matrix can be seen, even under eight hundred power magnification. An arbitrary distinction was made which classified grains greater than 0.05mm. in diameter as fragments, and everything smaller as constituting the matrix. Using this classification, these five samples are composed of an estimated ten to twenty per cent matrix material, and ninety to eighty per cent fragments.

In plane polarized light, the matrix, in most instances, appears light brown, grayish brown, or grayish green although in one case it is virtually colorless. The color is not uniform, and light and dark patches throughout the matrix are common; the darker patches usually occur in areas where the grain size of the matrix is extremely small. The color appears to be due to two minerals. Small, ragged, translucent, red grains, probably an iron oxide, are disseminated throughout the matrix. They do not contribute a great deal to the color, except where they occur as aggregates of cubic or rectangular grains up to about 0.2mm. in diameter. Most of the color is imparted by a dusty, granular alteration of the matrix, which cannot be resolved under eight hundred power magnification. This alteration is most prominent in the interstices between the matrix grains which can be resolved under high magnification; however it is also found on the surface of these grains.

No flowage or banding structures can be detected in this matrix composed of comminuted grains.

Grain size of the rock and mineral fragments in the breccias is extremely variable. Although the size of grains larger than 40mm. cannot be measured in thin sections, hand specimens reveal rock fragments as large as 1 foot or more in diameter. Thin section studies show that there is a complete gradation in grain size down to less than 0.01mm.; the average in most samples lying between 0.1mm. and 0.3mm. A visual estimate indicates that the roundness of the majority of grains matches that of the .2 and .3 classes of Krumbein's classification (Krumbein, 1941). That is, most grains are quite angular, and the erratics can be properly called breccia in contrast to a conglomerate.

These oligomictic breccias contain both rock fragments and mineral fragments. Thin sections of the various samples were selected to elucidate features of the matrix or the finer-grained fragments; as a result, the thin sections contain predominantly mineral rather than rock fragments, although thin sections of the latter also were studied.

The mineral fragments are chiefly quartz, plagioclase, and microcline, with accessory biotite, epidote, chlorite, sphene, and muscovite. Because of the large variation in grain size and the difficulty often encountered in distinguishing matrix from inclusions, the modes are only estimated and not point counted. Estimates indicate that quartz grains account for approximately sixty per cent of the mineral fragments. Microcline and plagioclase share about equally the remaining forty per cent.

The quartz grains are angular and show moderate to strong undulatory extinction; larger grains are commonly fractured. The walls of the fractures are in places separated sufficiently for them to be occupied by the comminuted matrix. In one thin section straight, sharp, parallel bands of material occur in the quartz grains with the highest birefringence. These bands are discussed in Chapter VI under the heading "Deformation Lamellae". Grains of microcline are microperthitic, containing small stringers of plagioclase. Fracturing, both irregularly and along cleavage planes, is more developed than in the quartz grains (see Figure 5-5). Extinction of several microcline grains is very patchy or undulose, and distortion of the polysynthetic twin pattern is common. Plagioclase feldspar grains are also fractured to a high degree, primarily along cleavage planes. Twin lamellae are commonly bent, truncated, or offset, and a weak undulatory extinction is developed in a few grains. Determination of the plagioclase composition by the Michel Levy method (Kerr, 1959) and the Rittmann zone method (Emmons, 1943) is difficult in these breccias, but crude measurements indicate that the plagioclase is an oligoclase, ranging in composition from about An_{12} to about An_{25}. One reliable determination, using Smith's technique (Deer, Howie, and Zussman, 1963) showed the plagioclase from a rock fragment in these breccias to be $An_{18 \pm 2}$.

Subhedral biotite plates occur rarely as individual fragments, but more commonly within the rock fragments. The brown biotite is usually ragged with undulating cleavage traces (see Figure 5-6). The parallel extinction displayed by undistorted biotite is often incomplete or patchy in these grains. Poorly defined bands that differ in extinction position from the overall grain form at an angle of approximately sixty degrees to the basal cleavage traces. Some chlorite alteration is present in all biotite grains.

Rock fragments in the breccias are essentially of a single type. They are massive or gneissic granitic rocks, similar to the granitic rocks of the Lac Couture region. Quartz grains show strong undulatory extinction; the microcline is a microperthite, the plagioclase is dominantly oligoclase; rims of myrmekite or albitic plagioclase are common along the margins between plagioclase and microcline grains. The interrelationship of these minerals creates an allotriomorphic-granular texture in the rock fragments. Chloritized biotite, epidote, sphene, muscovite, and zircon complete the mineral assemblage. Gneissic or banded structures cannot be detected in thin sections of the rock fragments, but can be seen in the hand specimens of the larger fragments.

Crystalline matrix breccias. The matrix of most of the breccia erratics examined is cryptocrystalline or microcrystalline. Although the crystallinity of the coarser varieties is readily discernible, in the finest-grained varieties this can only be assumed from uniformity of grain size and pin-point extinction. In contrast to the breccias already discussed, where the matrix constituted no more than twenty per cent of the rock, the matrix of this type is estimated to comprise between ten and ninety per cent of the rock. In other words, the amount of matrix material can be as little as ten per cent of the breccia. In general, those samples possessing the smaller proportion of matrix were taken from the large erratics, located near or on the islands of Lac Couture, although some of the small pebbles from sample location 16 (see Figure 2) also have this composition. On the other hand, all the specimens with a high percentage of matrix were found as pebbles on the gravel beach at location 16.

The grain size of the matrix constituents reaches a maximum of 1mm. in one of the pebbles. The matrix of other samples is commonly too fine-grained to detect individual grains at even eight hundred power magnification, and only pin-point extinction gives any evidence that the matrix is not glassy. Although no statistical correlation was made, the cryptocrystalline matrix appears to occur where the percentage of fragments is large, and a microcrystalline matrix where there are relatively few fragments.

An alteration of the cryptocrystalline varieties colors the matrix light gray brown, but the alteration is too fine-grained to determine its nature. The mineralogical composition of the matrix is difficult to determine even in the coarsest samples. The low birefringence (low first order interference colors) probably indicates siliceous rather than carbonate material, and the components are probably silica and feldspar. As the matrix grain size increases, simply-twinned microlites of feldspar can be identified. These microlites commonly occur in sheaf-like aggregates or as semi-spherulites (see Figure 5-4), but are also present in a felty texture. On the basis of the extinction angles of the microlites and their negative elongation, the feldspar is probably a plagioclase of approximately An_{25} composition.

Paralleling the feldspar laths in the sheaves or spherulites or intergrown in the matrix is an unidentified mineral. It is grayish green in color or altered to an orange brown, and may be simply a coarser variety of the alteration product described earlier. It usually is found in small laths with a low birefringence, parallel extinction, positive elongation, and moderate relief. Its small size may account for its apparent lack of pleochroism. The larger laths which are intergrown with the feldspar are really granular aggregates of equant crystals or short laths, arranged in linear fashion. It is this mineral which imparts the color to the crystalline matrices.

A mineral constituent in other specimens with a microcrystalline matrix is equant, has low first order interference colors, and is intergrown with the felty feldspar matrix. This mineral is likely one of the forms of SiO_2.

These three minerals are the only ones which can actually be seen as forming part of the matrix.

The matrix of the samples containing a high percentage of fragmental material simply occupies the spaces between fragments and usually possesses no other structural features. As the amount of fragmental material decreases, the matrix exhibits a number of textural variations. One of the most prominent of these is a definite banding within the matrix. This banding is created by parallel zones of crystals of different grain size. Zones of coarsely crystalline feldspar laths grade into finer-grained zones throughout the section (see Figure 5-2). No successive graded scheme occurs, however, and the grain-size banding is oscillatory. Although the banding is relatively straight and parallel, a gentle curvature of the zonation also occurs. Rarely the banding is quite sinuous and gives the impression that the matrix has flowed. Individual feldspar laths are distinctly bent to follow, or to create, this texture. The grain size of the cryptocrystalline matrix is usually uniform in samples where fragments predominate, but patches of coarser material, usually aggregates of feldspar laths, are present in places.

In one sample, where the feldspar laths occur as separate grains and not in sheaf-like or spherulitic aggregates, they together with laths of the unidentified mineral show a strong parallel orientation of their long directions. No foliation can be detected in the hand specimen of this sample.

Vesicles and filled cavities are abundant in varieties in which matrix material predominates. They can account for as much as an estimated twenty per cent of the rock, but generally they comprise in the neighborhood of five per cent. A great variety of shapes are exhibited by these cavities, but all those within the same thin section possess the same general morphology. Most of the vesicles and amygdules are distinctly circular or oval (see Figure 5-4) and average about 0.3mm. in diameter. Others are elongated or drawn out, usually parallel to the grain-size banding or flow banding. In these latter samples, vesicle- and amygdule-rich bands alternate with the more coarsely crystalline bands of the matrix. Some vesicles are irregular or amoeboid in shape (see Figure 5-3). The coarsely crystalline laths of the feldspar sheaves and spherulites are truncated by the cavities or bend around them (see Figure 5-4).

The filled cavities are more numerous than the vesicles. They are darker colored than the surrounding matrix, ranging from a light brown to a dark reddish orange. The amygdules are completely filled by a cryptocrystalline material, not unlike the surrounding matrix. Grain size of the components of this cryptocrystalline filling ranges from a maximum of 0.01mm. to practically glassy. Pin-point extinction and low birefringence are the only indications that the material is not isotropic. Uniformity of grain size and lack of textural

Figure 5-1. Breccia (plane light, x10).

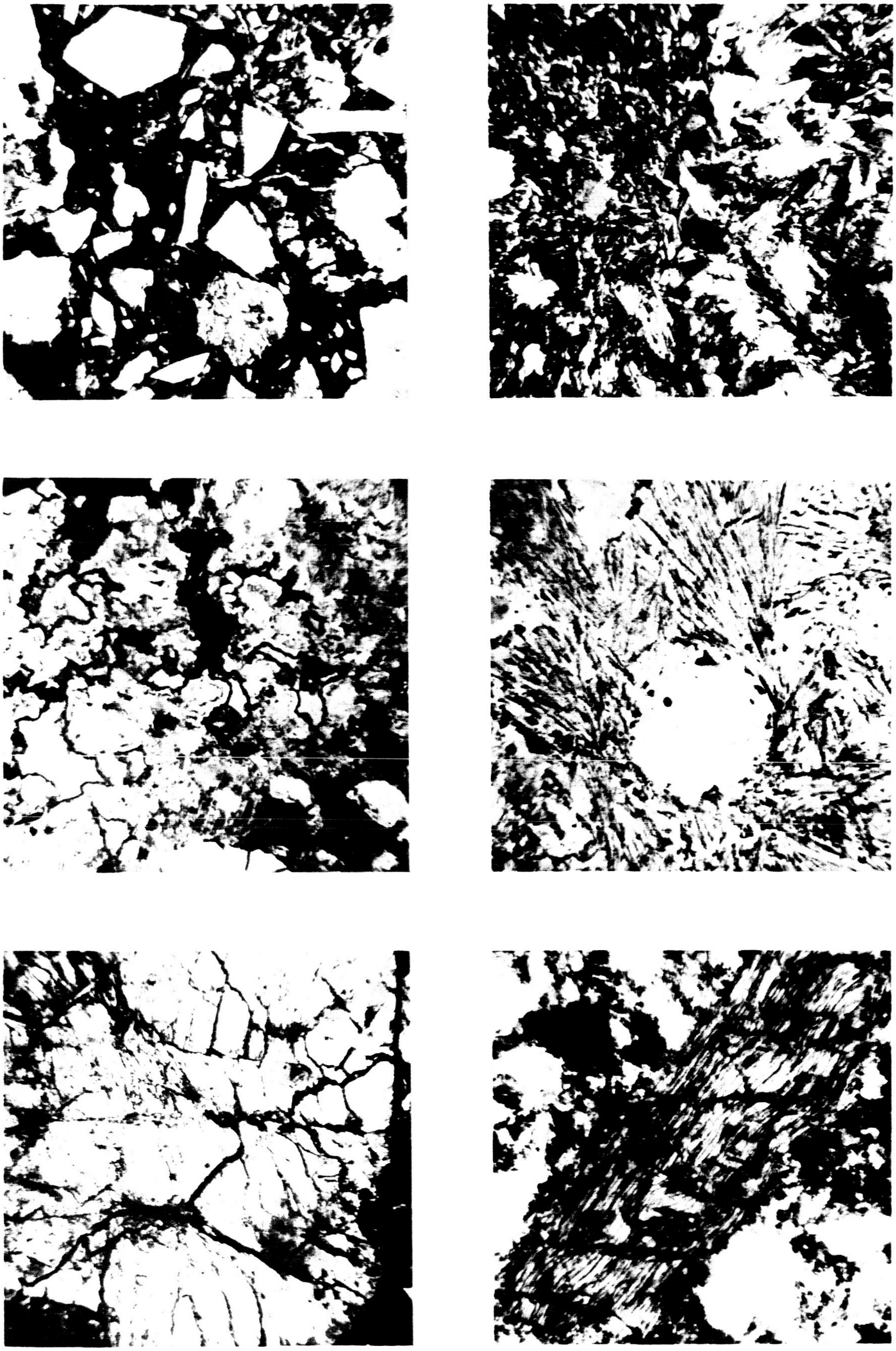
Figure 5-2. Feldspar laths in cryptocrystalline matrix showing grain size banding (crossed nicols, x35).

Figure 5-3. Distorted amygdules in breccia (plane light, x35).

Figure 5-4. Feldspar spherulites and amygdule in breccia (plane light, x35).

Figure 5-5. Fractured microcline grain in breccia (crossed nicols, x40).

Figure 5-6. Distorted biotite grain in breccia (plane light, x150).



variation within these amygdules render their interiors virtually structureless.

The mineralogy of the cryptocrystalline interiors cannot be determined due to the minuteness of the grains, but the low birefringence indicates that it is probably siliceous, rather than carbonate. The similarity between the amygdule interiors and the cryptocrystalline matrix of the breccia would make it practically impossible to distinguish the two were it not for the difference in color. This brown, yellow, or reddish orange color of the amygdules is due to what appears to be an alteration or staining of minute spherulitic growths. These spherulites form along the margins of the cavities, but are within the cryptocrystalline material and are not attached to the walls. The dark orange amygdules contain these spherulites throughout their interiors, obliterating the underlying material. The crystals of the spherulitic growths are, perhaps, grayish green, but are tinted orange by an iron oxide stain. They have parallel extinction, positive elongation, middle first order interference colors, and resemble a chlorite, except for their length-slow characteristic. Anhedral grains of an isotropic mineral, which appears black or reddish brown in plane polarized light and is probably an iron oxide, are present throughout the amygdules, where they are commonly concentrated along the margins.

Euhedral quartz crystals grow inward from the walls of the amygdules, but do not fill the cavity. Usually only three or four crystals are found in each cavity. The spherulites rim the unattached margin of the quartz crystals.

In addition to the cryptocrystalline matrix, the area between the fragments of one specimen is filled by microcrystalline chalcedony. The chalcedony is in colloform, accretionary bands, which vary from colorless to dark reddish brown. The center of the cavities or channels lined by the chalcedony are filled with coarser, interlocking, quartz grains.

In several places narrow (less than 0.01mm.), sinuous veins of quartz cut through both the matrix and fragments.

It is perhaps best to refer to the other constituents of these breccias as inclusions, rather than fragments, because certain inclusions within the matrix do not appear to be part of the matrix, and do not possess the characteristics of fragmented material. The fragments of this second type of breccia are similar to those described in the comminuted matrix type. Angular quartz, plagioclase, and microcline comprise the bulk of the fragments, with minor amounts of biotite, chlorite, epidote, muscovite, and sphene. Fractures and other deformation features described previously occur in these fragmented grains. Deformation lamellae are commonly encountered in quartz grains, and also rarely in plagioclase grains (see Chapter VI). Optic axial angle measurements on potash feldspars indicate that the majority are microcline. Four grains, however, yield values for $2V_{\alpha}$ between 32° and $38^{\circ} \pm 5^{\circ}$ (see Appendix D). These grains exhibit very low birefringence (first order gray interference colors), are highly fractured, and have a dusty brown alteration.

Fragments of plagioclase often contain cores or patches of cryptocrystalline material within their interiors. Isolated patches of the feldspar, separated from one another by the cryptocrystalline material, are in optical continuity with each other, and the orientation of the albite twin lamellae is also consistent. The constituent minerals of the cryptocrystalline material are too small to be identified, even under eight hundred power magnification. A dusty green color of the cryptocrystalline patches is due to a minute, unidentifiable, alteration product. Patches of reddish brown material are scattered throughout the cryptocrystalline material and, although they are ragged, seem to be controlled by remnant twin lamellae of the plagioclase. In some cases, no plagioclase remnants are left, but inclusions composed entirely of the cryptocrystalline material possess outlines reminiscent of the feldspar cleavage. The reddish alteration is crudely confined to narrow parallel bands within these inclusions. The interior of these inclusions appears identical to the surrounding matrix of the breccia, and the two would be indistinguishable were it not for the dusty green alteration of the former and their microcrystalline outlines. The rim of these inclusions is the same unidentified mineral described earlier as forming in spherulitic growths in the amygdules. In this case no spherulites occur, but needle-like crystals grow inward to the interior of the inclusions.

Another type of inclusion appears to be fragments of breccia. Once again it is difficult to distinguish between the cryptocrystalline matrix of the breccia and the cryptocrystalline material of the inclusion. Angular fragments, primarily of quartz, occur within these inclusions and make them appear to be breccia fragments. The boundary between an inclusion and the matrix is marked by a zone of reddish brown alteration. This zone is distorted and incomplete, and the alteration extends in places well into the matrix. Thus the margin is not sharply defined and is even gradational. These inclusions are elongate, and bands of the alteration product paralleling the length create a flowage appearance.

Figures 6-1, -2, -3, and -4 are examples of another group of inclusions which do not appear to be fragmental in nature. The inclusions are not angular, but have oval or rounded irregular shapes; the margins are usually sharply defined, but in places are embayed by the cryptocrystalline matrix of the breccia. The intruding tongues of the matrix do not appear to have replaced the material of the inclusion, but have been emplaced in fractures (see Figure 6-2).

The material of these inclusions is entirely microcrystalline silica in one form or another. Grain size varies greatly between inclusions and within single inclusions. Some are composed of anhedral microcrystalline quartz grains less than 0.01mm. in size in a highly interlocking texture, and thus appear to be chert fragments. Others are made up of only three or four large quartz grains in a similar texture and show extreme undulatory and patchy extinction. Still others contain grains ranging in size from less than 0.01mm. to about 0.5mm. A few zones or veins of radiating chalcedony occur within the finer-grained examples, whereas radial aggregates of coarser quartz are

Figure 6-1. Curved fractures in inclusion in breccia (plane light, x35).

Figure 6-2. Intrusion of matrix into inclusion in breccia (plane light, x40).

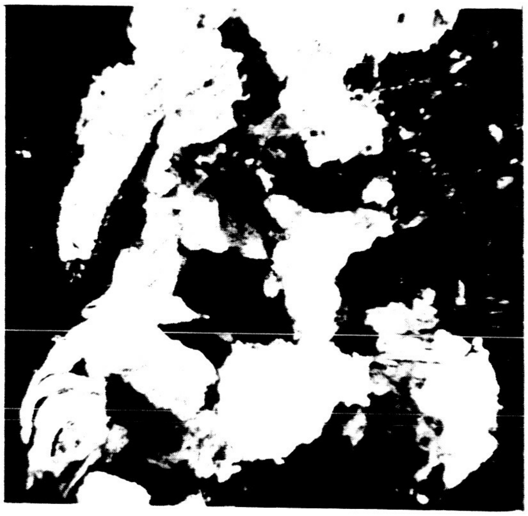
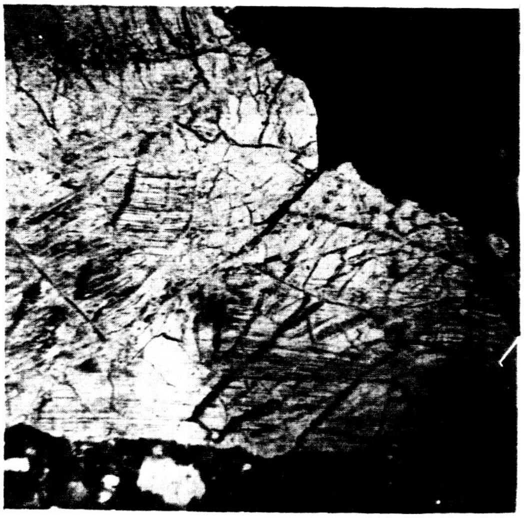
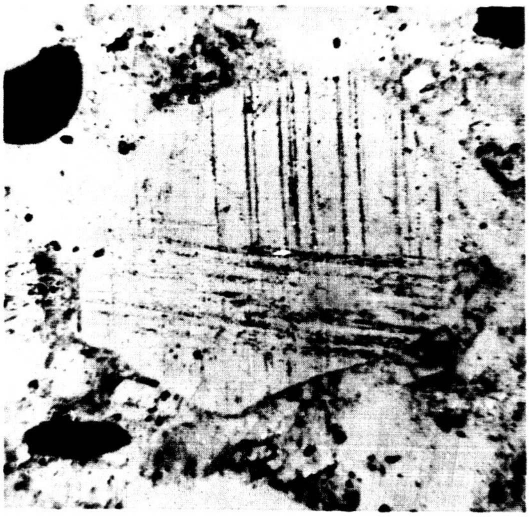
Figure 6-3. Thumb-print texture in breccia (plane light, x40).

Figure 6-4. Thumb-print texture in breccia (crossed nicols, x40).

Figure 6-5. Deformation lamellae in quartz grain in breccia (plane light, x35).

Figure 6-6. Deformation lamellae in quartz grain in breccia (plane light, x150).



present in others. Curved fractures (see Figure 6-1) are prominent features of a large percentage of these inclusions; these are best observed in plane polarized light. Under crossed nicols the fractures do appear to separate areas of discontinuous optical properties, but do not separate actual grains. Where they are present in inclusions containing only few large grains, they seem to bear no relationship to the optics or outlines of the grains.

A "thumb print" texture is exhibited in several of these inclusions (see Figures 6-3,-4). Sinuous bands and sworls of granular aggregates of material too fine-grained to be identified create this texture. Parts of the bands are composed of isotropic material, whereas other parts are predominantly liquid inclusions. The texture does not appear to be related to the optics or crystal outlines of the quartz grains of the inclusions (see Figure 6-4).

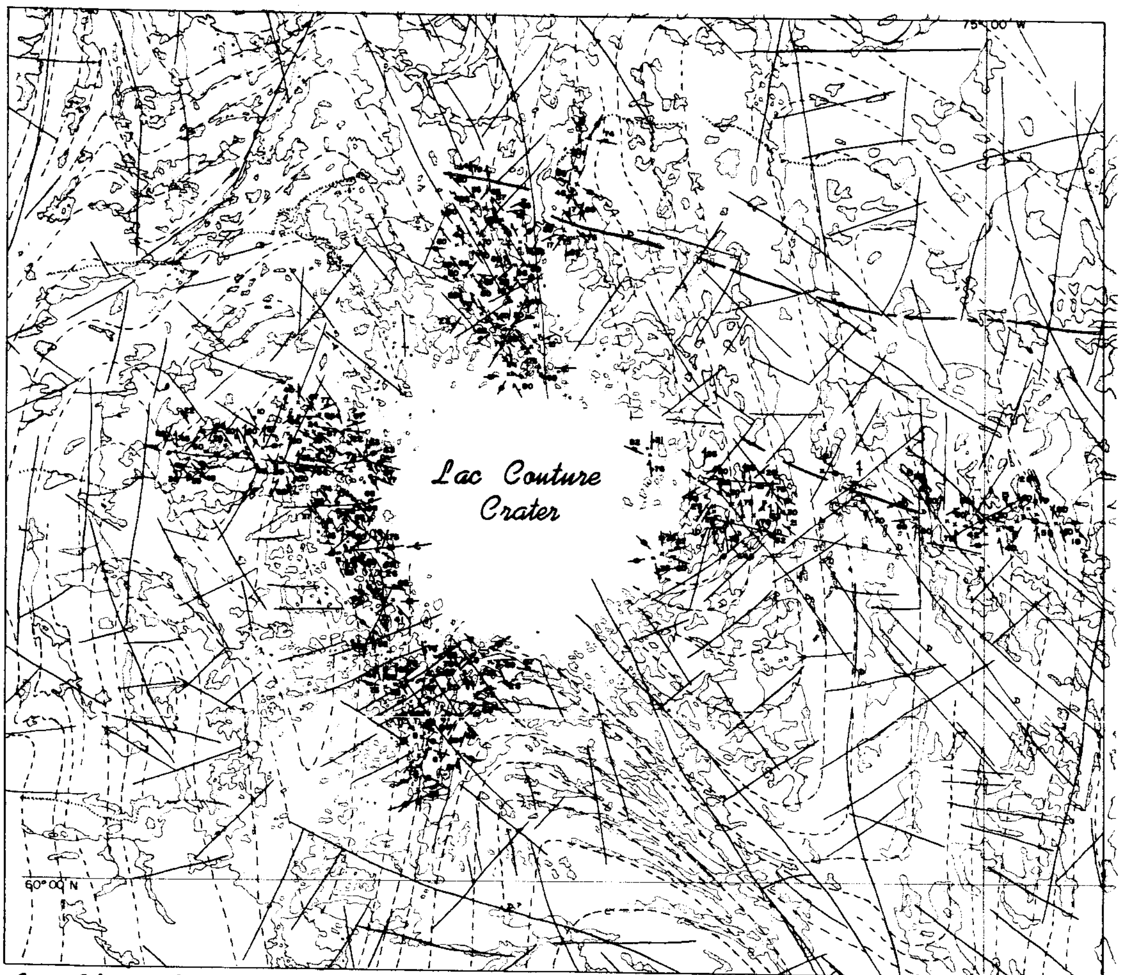
CHAPTER IV

REGIONAL STRUCTURE

The limited time available for geological investigations in the vicinity of Lac Couture restricted the data gathering procedures to certain aspects. Prime among these was the collection of orientated samples from as widespread an outcrop area as possible. Concurrently perfunctory observations were made on the petrography of the rocks encountered, with the knowledge that a more intensive study would be carried out on the thin sections of the samples collected from these outcrops. Structural data, however, had to be recorded in situ, and it is this aspect that has suffered most as a result of the limited time alloted to its accumulation. The attitude of foliations, lineations, geological contacts, sheeting joints, and other joints were measured where visible, and the values can be found plotted in Figure 7.

D. P. Gold (1965) compiled a structural interpretation of the geology around Lac Couture from 1 inch = 3,560 feet scale aerial photographs (see Figure 7). A series of north-northwesterly trending concentric folds have been constructed from inferred geological contacts. These contacts are probably observed in the field as strongly foliated or gneissic zones within the generally poorly foliated country rock. A large number of lineaments have also been plotted in Figure 7, which Gold interpreted as traces of fracture and joint planes. Some of these lineaments may be the surface expression of diabase dykes. The mapped diabase dykes (see Figure 7) do not appear to have been

Figure 7. Air photo interpretation of the structural geology for the area surrounding the Lac Couture Crater (after D. P. Gold).



Air Photo Interpertation of the Structural Geology for the Area Surrounding the Lac Couture Crater, Quebec.

SYMBOLS

Lineaments (trace of fracture & joint planes)

Inferred geological contacts (gneissic banding & foliation)

a b (a) Esker (b) glacial striae

x Outcrop at which geological observations were made

a b Strike & dip of gneissosity (a) inclined (b) vertical

a b Strike & dip of major joints planer (a) inclined (b) vertical

a b Strike & dip of sheeting joints (a) inclined (b) vertical

a b Strike & dip of shear zones

a b Plunge of (a) 'b' lineation (b) drag folds

a b Axis of folds (a) antiform (b) synform

Lake

ROCK TYPES

Diabase

Mainly massive course-grained granite gneiss, quartz-feldspar-biotite gneiss, with lesser amounts of quartz-feldspar-epidote gneiss, quartz-feldspar-mica schist, and enclaves and schlieren of amphibolite.

Scale 0 1 2 3 4 5 Miles

D. P. Gold, 1964

affected by the inferred folds. This is indicated by the fact that they transect the folds and are not bent or folded in any noticeable manner, even in the regions of maximum flexure.

Although no evidence was discovered in the field to indicate the presence of major faults, it seems likely that one runs northward along the valley which contains the northern inlet to Lac Couture (see Figure 7). The western extension of the largest mapped diabase dyke has been relatively offset to the north by a distance of about one half mile.

In an area in which the drainage pattern is controlled by glaciation and by bedrock (most notably in the southeast corner of Lac Couture), this circular body of water is unique. The limbs of the supposed folds do not bend around Lac Couture, but instead are terminated by it, and perhaps can be traced to reappear on the opposite side of the lake. In other words, Lac Couture has been superimposed upon an already existing regional structure.

Foliation and Gneissosity

A weak foliation is exhibited by a few of the granitic rocks in the Lac Couture vicinity. This structural element becomes more pronounced in some of the granitic rocks underlying the shallow topographical valleys, and is well developed in the bands or enclaves of amphibolite and in biotite and chlorite schists. The foliation is due to the planar arrangement of the platy minerals, such as biotite, chlorite, and muscovite (see Chapter III). A gneissic banding is more common than foliation in the granitic rocks, and its attitude can be measured in most outcrops.

The strike and dip of these two planar structures were measured in the field (see Figure 7) and later plotted in stereographic projection (see Figure 8-1). This projection was contoured using Schmidt's method (Turner and Weiss, 1963). The seventy-six points plotted indicate a distinct overall strike for the gneissic banding and foliation of approximately north-northwest. The majority of dips have values between seventy and ninety degrees and are distributed nearly equally between those dipping to the west and those dipping to the east. A smaller number of points forming a rough girdle represent planes dipping shallowly to the south-southeast at angles close to twenty degrees.

The general trend appears to coincide with Gold's interpretation. The planes dipping at high angles to the east and west are from samples lying on the limbs of the folds, and the south-southeasterly dipping planes are from samples located on the noses of the folds. These latter values, plus the almost complete absence of northerly dipping planes, suggest that the series of antiform and synform folds plunge at a moderate angle to the south-southeast.

The attitude of the gneissic banding superimposed on the inferred structure (see Figure 7) confirms these assumptions. Values of dip and strike, obtained from samples located near the nose of the fold on the south shore of Lac Couture, reveal that it is a synform fold. East- and west-dipping gneissic banding on the limbs of the other folds of the area agree with the rigid alternation of antiform and synform folds. The south-southeast plunge is also in accord with the directions in which the noses of the two types of folds point.

Lineations

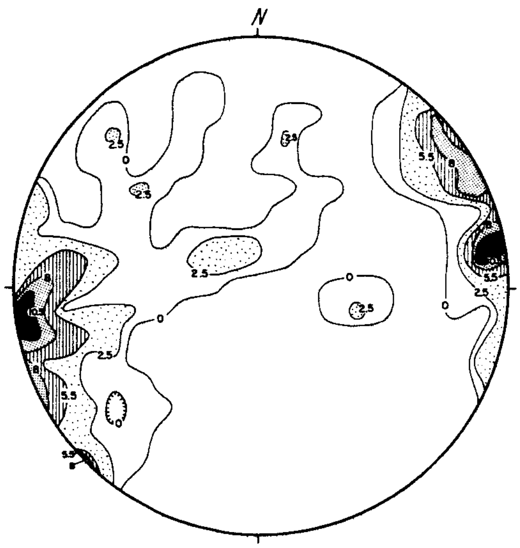
Lineations produced by the parallel alignment of minerals or amphibolite boudins and by the axis of drag folds are present in the granitic rocks. The attitude of these linear features was measured in the field (see Figure 7) and then plotted on a stereographic projection (see Figure 8-2) which was contoured by Schmidt's technique (Turner and Weiss, 1963). A definite grouping of the points plotted indicates that almost all the lineations plunge to the southeast, at an angle of approximately sixty degrees to the horizontal. This attitude agrees with the overall regional trend, inferred from aerial photographs, and from the banding and foliation measured in the field.

Sheeting Joints

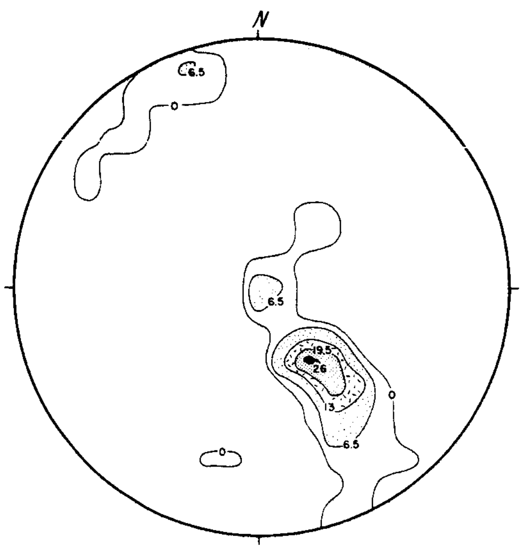
Sheeting surfaces are planar joints which are essentially parallel to the topographic surface of the region. According to the most widely held hypothesis, sheeting is due to release of load during erosion. As a consequence of the decrease in confining pressure, the rock expands in all directions. The horizontal expansion is impeded by the surrounding rock, but vertical expansion is unhindered, except by the air. The compressional forces resulting parallel to the earth's surface would create shear fractures inclined at about thirty degrees to the surface, and extension fractures. The latter would be parallel to the surface of the earth and appear as sheeting joints (Billings, 1954).

Figure 8-1. Gneissosity and foliation in the gneisses of the Lac Couture region.

Figure 8-2. Lineations in the gneisses of the Lac Couture region.



I. Contours 0-2.5-5.5-8-10.5 % per 1% area (76 points)



2. Contours 0-6.5-13-19.5-26% per 1% area (31 points)

Sheeting joints in the Lac Couture region are not well developed, and in most outcrops this surface cannot be detected. Where they were visible, the attitude of the sheeting joints was measured in the field (see Figure 7), and the values were plotted on a stereographic projection. An attempt was made to detect any variation in this feature outward from the lake (see Chapter V). The results will be presented in more detail in Chapter V, and it is sufficient here to state that the sheeting joints coincide generally with the topography and dip gently in all directions (see Figure 10).

Subvertical Joints

The attitude of the subvertical jointing encountered in the granitic rocks, amphibolites, and diabase dykes was measured in the field (see Figure 7). These measurements were plotted on a stereographic projection, and contoured by Schmidt's method (Turner and Weiss, 1963) (see Figure 11-3). An attempt was made to detect any regional variation in the joint systems, and results of this study are recorded in Chapter V. From Figure 11-3 it can be seen that the majority of joints are steeply inclined to the horizontal, and dips of between seventy-five and ninety degrees predominate.

Although joints strike in all directions in the rocks around Lac Couture, three sets may be identified. One set strikes north and dips steeply to the east or west; another set strikes east and also dips steeply to either side; a third set strikes approximately 110° true and likewise dips steeply to either side. In between these poorly defined maxima a radial arrangement of jointing exists.

CHAPTER V

SYSTEMATIC VARIATIONS IN STRUCTURE

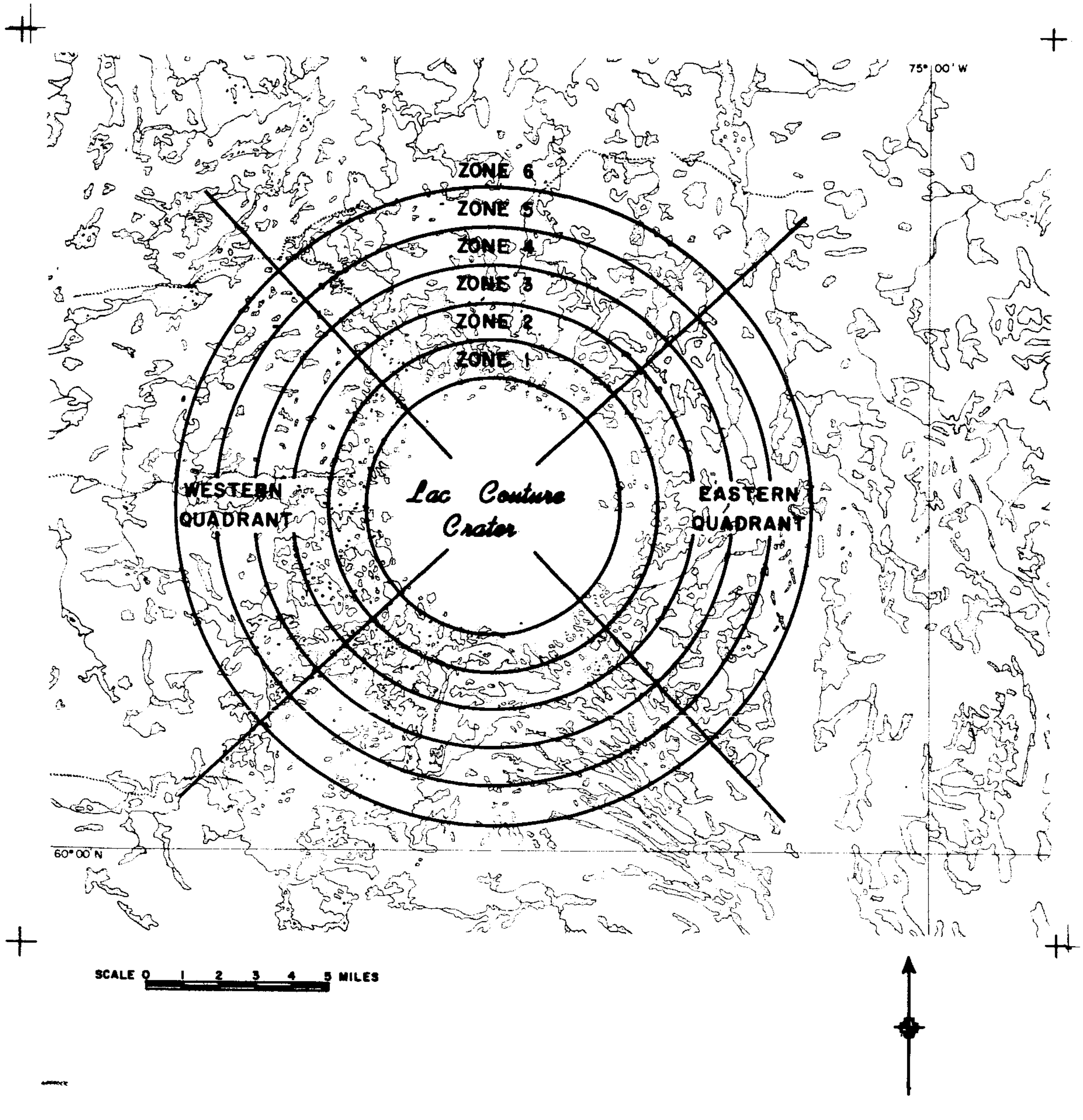
If the crater occupied by Lac Couture had been created by the impact of a meteorite, it would be reasonable to believe that changes would be created in the structural state of the country rocks, both on the regional and atomic scales. The intensity of these changes should be most pronounced near the point of impact and would die out rapidly as the distance from this point increased. On the basis of this assumption, the variation of four structural parameters was analyzed as a function of distance from the geometrical center of Lac Couture. These four are sheeting joints, other joints, undulatory extinction in quartz, and the structural state of potash feldspar.

Sheeting Joints

The geometrical center of Lac Couture was approximately located by inscribing a circle within the ring of islands in the lake. A series of six concentric zones were constructed about this center; the innermost zone, number one, extends from the lake's edge to one mile beyond the inner ring of islands, and successive zones are built up in increasing radius increments of one mile. The outer zone includes the area lying more than eight and one-half miles from the center (see Figure 9).

The regional picture of the attitude of the sheeting joints has been presented in Chapter IV: they conform in general to the topography and are subhorizontal. No visible topographic expression of a

Figure 9, Division of the Lac Couture region into radial and concentric zones.


ZONE 6
ZONE 5
ZONE 4
ZONE 3
ZONE 2
ZONE 1
WESTERN QUADRANT
EASTERN QUADRANT
Lac Couture Crater
75° 00' W
60° 00' N
SCALE 0 1 2 3 4 5 MILES

rim can be seen around Lac Couture. The smallest scale topographic maps (one inch = four miles) do not contain sufficient contour information in this region to enable one to detect such a feature from these maps. The sheeting joints represent the original topography, and formation of a rim by any process would cause an upheaval in these joints so that they would dip tangentially outward around the crater. This fact has been demonstrated by Gold (1965) for the sheeting joints in the rim of the New Quebec Crater.

In order to determine whether or not a rim did exist around Lac Couture prior to glaciation, the attitude of the sheeting joints from outcrops lying within zone one were plotted on a stereographic projection. Similar plots were made for each of the other five zones, and the diagrams were contoured by Mellis' technique (Turner and Weiss, 1963). The plots for zones three, four, and five were combined after a visual inspection revealed no difference between them. Figures 10-1, -2, -3, and -4 are the contoured plots for zones one, two, three, four, five, and six, respectively. The diagrams for all zones, except zone two, are similar. They indicate that the sheeting joints in these areas are flat-lying or have shallow dips in all directions about the center.

The sheeting joints of outcrops lying within zone two do not conform to this regional pattern. There are no horizontal joints, and an annulus of points about the center of the diagram indicates that the majority of joints are inclined at approximately fifteen degrees to the horizontal. The eleven per cent contour shows that most of the sheeting joints dip to the north, east, or west, and that few dip to the south.

If the sheeting joints of zone two are to be interpreted as the remnants of a rim then the northerly dipping joints should lie in the northern quadrant, the westerly dipping joints should lie in the western quadrant, and so on. Because there are so few sheeting joints recorded from this zone (twenty-six), any attempt to correlate the direction of dip and the quadrant of outcrop would be of no significance. Thus the only statement that can be made regarding the sheeting joints of zone two, is that they are not horizontal, and that most dip to the north, east, or west at shallow angles.

If zone two does represent a remnant rim, then the outcrops of zone one - primarily on islands - would lie within the rim or form part of the rim. The sheeting joints of zones one and two were combined in Figure 10-5 and the semi-annular distribution is still evident. Combining the sheeting joints from zones three, four, five, and six, produced Figure 10-6 which will represent the regional attitude of the sheeting joints described in Chapter IV.

Subvertical Joints

A severe shock produced by the impact of a meteorite would cause fracturing and jointing to occur in the country rock. The pattern and attitude of the joints will bear some direct relationship to the morphology of the crater. Meen (1957) reported that three sets exist in the rim rocks of the New Quebec Crater. In addition to the sheeting joints there is a set radiating outward at approximately right angles to the circumference, and the other set is circumferential.

Figure 10-1. Sheeting joints, zone one.

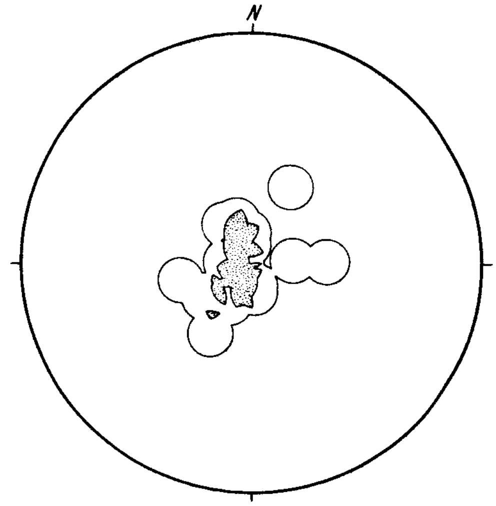
Figure 10-2. Sheeting joints, zone two.

Figure 10-3. Sheeting joints, zones three, four, and five.

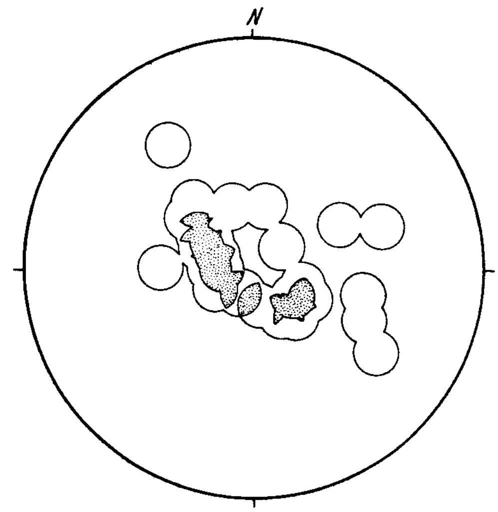
Figure 10-4. Sheeting joints, zone six.

Figure 10-5. Sheeting joints, zones one and two.

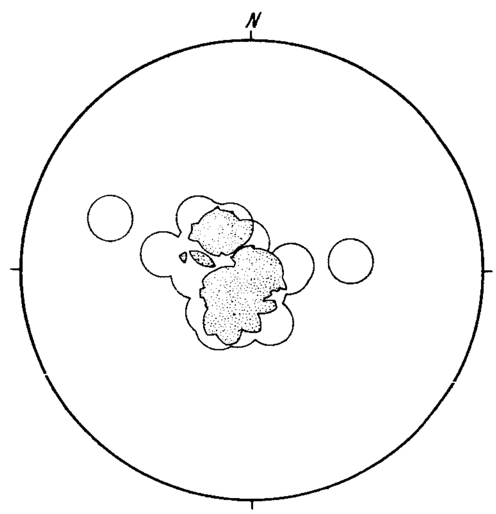
Figure 10-6. Sheeting joints, zones three, four, five, and six.



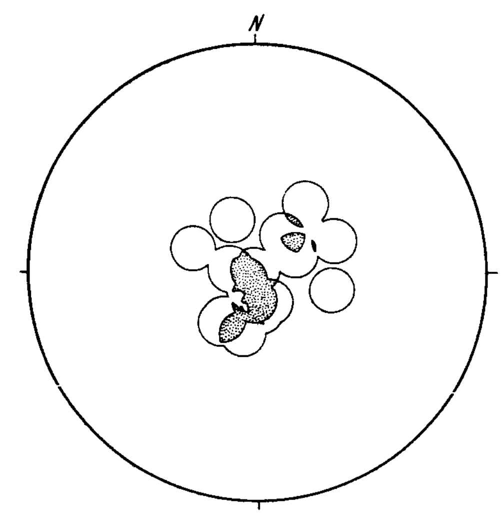
1. Contours 6 and 20 % per 1 % area (16 points)



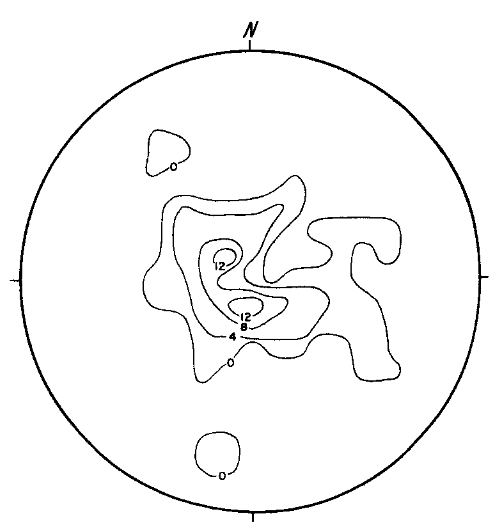
2. Contours 4 and 11 % per 1 % area (26 points)



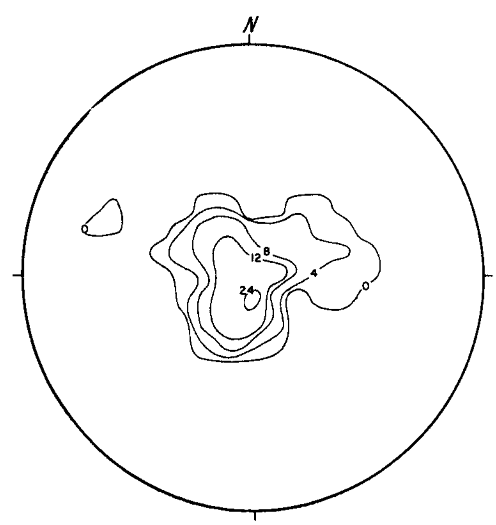
3. Contours 4 and 11 % per 1 % area (27 points)



4. Contours 6 and 20 % per 1 % area (17 points)



5. Contours 0-4-8-12 % per 1 % area (42 points)



6. Contours 0-4-8-24 % per 1 % area (44 points)

Gold (1965) agrees with this and reports one set parallel to the radius of the circular crater and a concentric set perpendicular to the radius. Surrounding the supposed crater of Deep Bay, Saskatchewan, Innes, Pearson, and Geuer (1964) have noted a random arrangement of lineaments but with a prominent set more or less radial to this circular feature. In addition, a system of concentric fractures has developed around parts of Deep Bay.

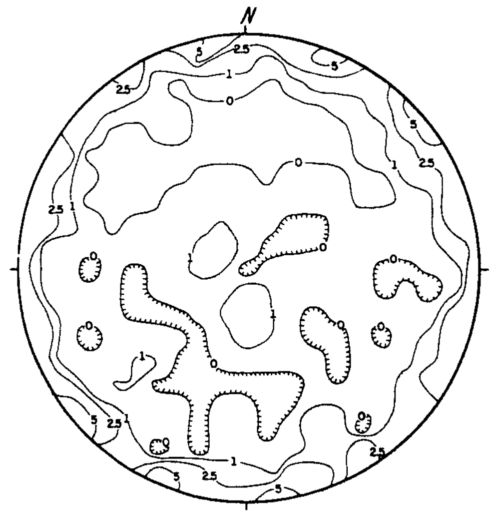
If these two prominent sets of fractures or joints, one radiating from the center of the lake and the other circumferential to it, can be found around Lac Couture, it would add another thread of evidence in support of its origin by a centrally located explosion. In an attempt to discover if such a pattern does exist, the attitude of the joints from a particular area was compared to those from another area. For this purpose the area around Lac Couture was divided into eight sections (see Figure 9), and separate stereographic projections were constructed for the joints in each of these zones. The regions in which geological observations were made, east, west, north, and south, serve as a natural subdivision into four sections. Each of these was subsequently divided into the area included in zones one and two discussed under sheeting joints, and the area outside of this, zones three, four, five, and six. The corresponding eight stereographic projections (see Figures 12-1a, -1b, -2a, -2b, -3a, -3b,-4a, and -4b) were contoured by Schmidt's method (Turner and Weiss, 1963).

As a means of comparison of the attitude of the joints in the inner concentric zone with those in the outer concentric zone, Figures 11-1 and 11-2 were compiled. The former plots the joints of

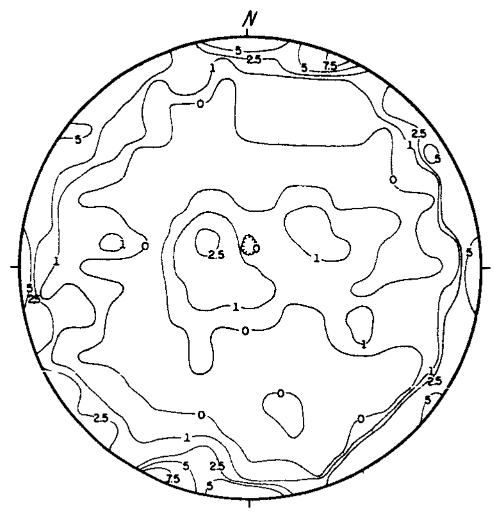
Figure 11-1. Subvertical joints, zones one and two.

Figure 11-2. Subvertical joints, zones three, four, five, and six.

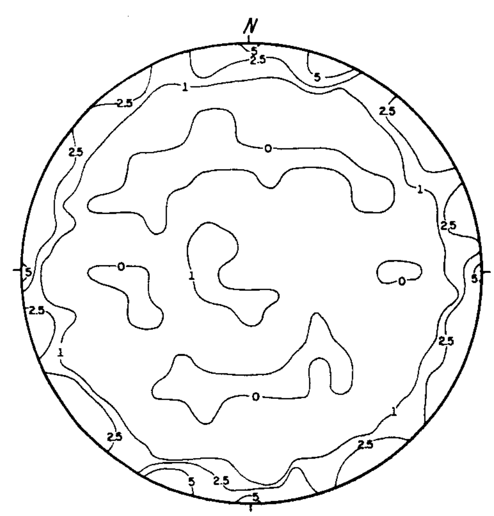
Figure 11-3. Subvertical joints, zones one to six inclusive.



I. Contours 0-1-2.5-5 % per 1% area (289 points)



2. Contours 0-1-2.5-5-7.5 % per 1% area (251 points)



3. Contours 0-1-2.5-5 % per 1% area (540 points)

the four quadrants lying within the inner zone and the latter is the similar plot for the outer zone. All the joints were then plotted on Figure 11-3 which will serve to represent the overall picture.

The latter diagram indicates that joints dipping between seventy-five and ninety degrees trend in all directions in the countryside surrounding Lac Couture. Three more pronounced trends do exist, however. One set of joints strikes north-south and dips steeply to either side; another set strikes east-west and also dips steeply to either side; a third set strikes approximately 110° true and likewise dips steeply to either side.

The joints lying in zones three to six inclusive also dip between seventy-five and ninety degrees and strike in all directions. The north, east, and 110° true sets are similarily found on this diagram. In addition, a set appears striking approximately 040° true with the same high inclination, and another at 150° true dips between seventy-five and eighty degrees southwest.

The joint pattern of zones one and two does not have the same symmetry as in the other two plots. Once again the joints are mostly steeply dipping, and trend in all directions. Three major sets can be detected. The 110° true set still exists, and the east set is slightly offset and strikes approximately 080° true. The north set is not developed, and an additional set striking approximately 140° true is present.

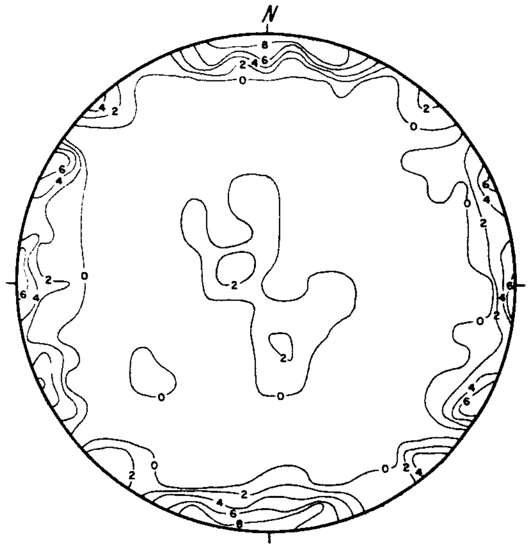
Examination of the four diagrams of the joints lying within zones one and two shows that the three sets are present in all four quadrants.

Figure 12-1a. Subvertical joints, northern quadrant, zones one and two.

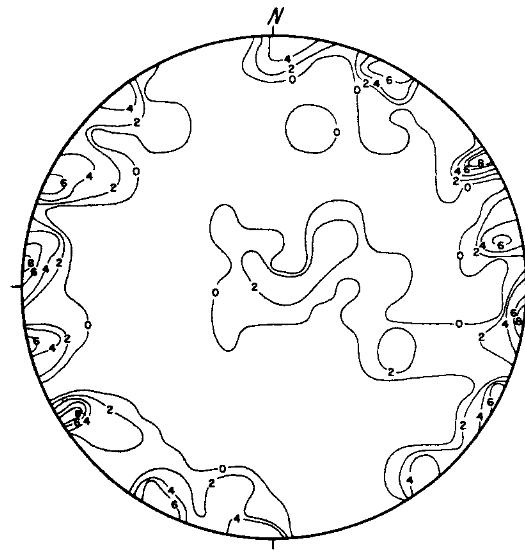
Figure 12-1b. Subvertical joints, northern quadrant, zones three to six.

Figure 12-2a. Subvertical joints, eastern quadrant, zones one and two.

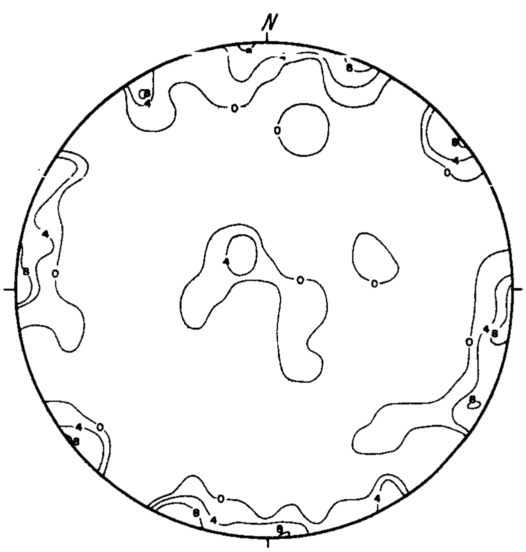
Figure 12-2b. Subvertical joints, eastern quadrant, zones three to six.



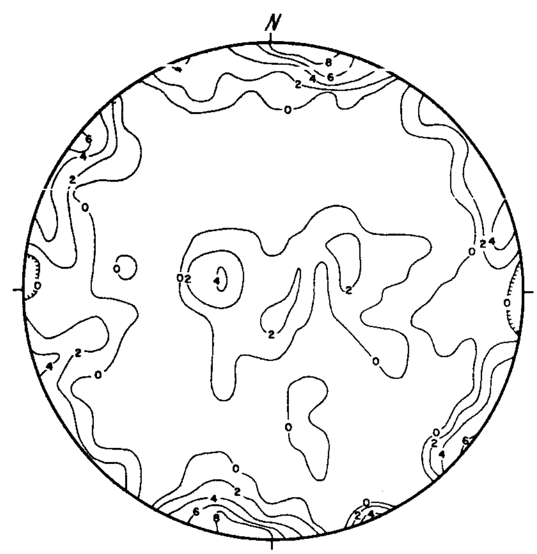
1a. Contours 0-2-4-6-8 % per 1% area (83 points)



1b. Contours 0-2-4-6-8 % per 1% area (57 points)



2a. Contours 0-4-8 % per 1% area (38 points)



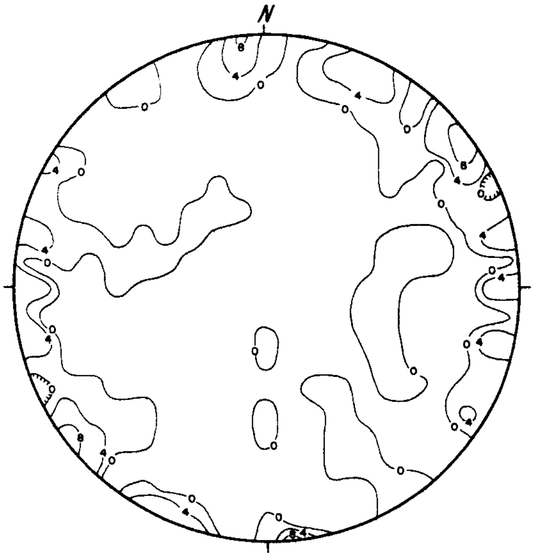
2b. Contours 0-2-4-6-8 % per 1% area (97 points)

Figure 12-3a. Subvertical joints, southern quadrant, zones one and two.

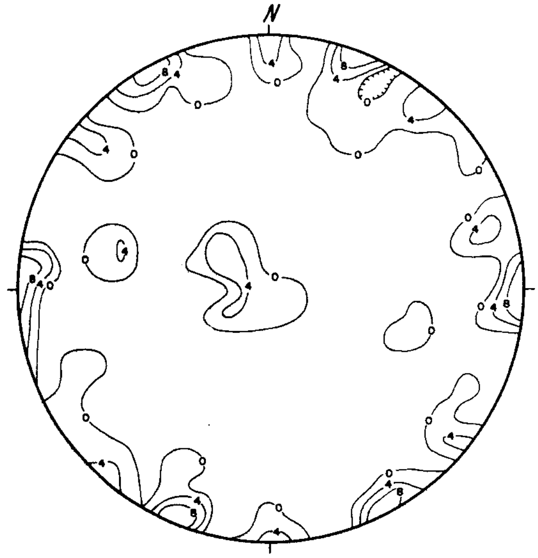
Figure 12-3b. Subvertical joints, southern quadrant, zones three to six.

Figure 12-4a. Subvertical joints, western quadrant, zones one and two.

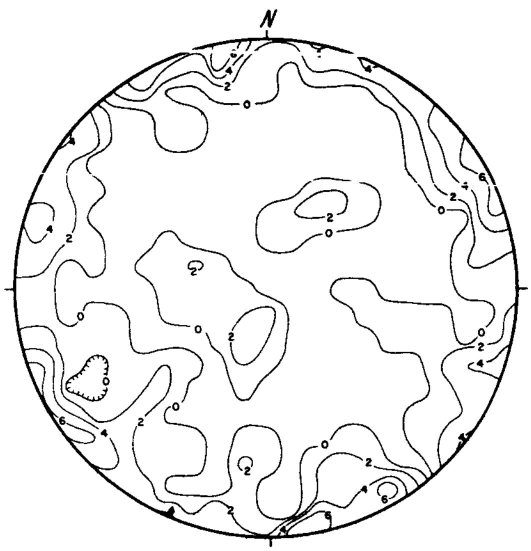
Figure 12-4b. Subvertical joints, western quadrant, zones three to six.



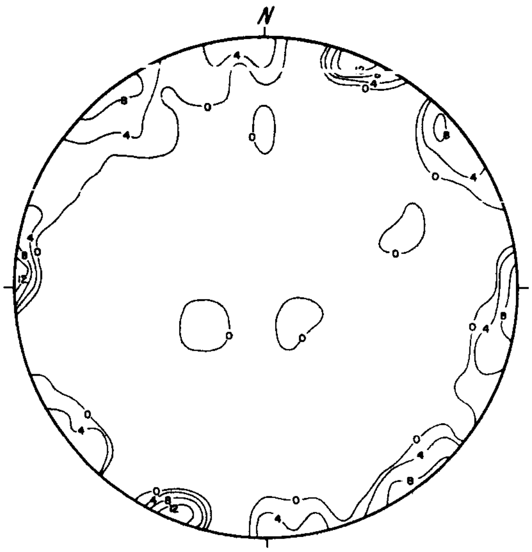
3a. Contours 0-4-8 % per 1 % area (62 points)



3b. Contours 0-4-8 % per 1% area (50 points)



4a. Contours 0-2-4-6 % per 1 % area (106 points)



4b. Contours 0-4-8-12 % per 1 % area (47 points)

A similar comparison for the outer zone also matches the composite picture, and the jointing pattern does not appear to differ appreciably from one quadrant to another.

Although a radial and circumferal pattern cannot be definitely ascribed to the joints of zones one and two, there does seem to be a marked difference in the jointing pattern between the inner and outer concentric zones.

Undulatory Extinction

The cause of undulatory extinction in quartz and other minerals has been the subject of many studies since the latter part of the nineteenth century. In a review of a number of these investigations on quartz, Griggs and Bell (1938) relate that most zones of undulatory extinction are sub-parallel to the c-crystallographic axis. Various authors had reported differences in extinction positions up to seventy degrees, and grains in which the direction of displacement was not constant but reversible. The variations of extinction position within a quartz grain are the expression of corresponding variations in the position of the optic axis (Griggs and Bell, 1938). Such crystallographic variations were attributed by most people to plastic deformation within the quartz at some time following crystallization. In order to simulate conditions under which plastic deformation would occur in quartz, Griggs and Bell, (1938) subjected quartz grains to various combinations of temperature and pressure. The only evidence for this distortion was the appearance of weak undulatory extinction in grains subjected to twenty thousand atmospheres pressure at four hundred degrees centigrade. Only one per cent of these grain exhibited this feature, and the maximum variation was only seven degrees.

Bailey, Bell, and Peng (1958) examined quartz grains from rocks of reportedly igneous origin and from others which had been subjected to regional metamorphism. They found weak strain shadows in the quartz from both these environments, except in the cases where it was believed that the quartz had been recrystallized. They concluded that marked wavy extinction is characteristic of deformed rocks irrespective of mode of origin of the rock. Plastic deformation was cited as the cause of this feature, and the maximum displacement could be viewed only when the axis of bending, an a-axis, was vertical.

Carter, Christie, and Griggs (1964) measured the undulatory extinction positions in quartz grains from undeformed St. Peter sand. After subjecting the samples to varying combinations of temperature, pressure, and time a definite increase in the degree of undulatory extinction was noted. Although the authors do not attempt to correlate the degree of development of this feature with any of these three parameters, examination of their results seems to indicate that the pressure factor exercises the greatest influence. An increase in pressure at constant or decreasing temperature strengthens the appearance of undulatory extinction.

Undulatory extinction in the quartz grains of the granitic rocks and breccias around Lac Couture has been described in Chapter III. This feature varies in intensity from vague shadows to narrow, sharply defined bands, subparallel to the c-axis of the grain. The distinct bands are called deformation bands by Carter, Christie, and Griggs (1964), but they admit that the division between undulatory extinction and deformation bands is arbitrary and that the two grade into one another.

Because pressure does seem to be a major factor in the formation of undulatory extinction, and if Lac Couture was created by a major shock, the degree of undulatory extinction might be strongly developed nearest the lake, and decrease in intensity outwards. In an attempt to discover if this relationship exists, the degree of undulatory extinction of quartz grains was measured in thin sections from nine breccia specimens and ten samples of the granitic rocks. The latter samples were chosen from outcrops located at increasing distances from the center of Lac Couture.

Measurements were made as follows. Quartz grains were selected which had first order yellow interference colors, as an approximation to grains whose c-axis was horizontal. On a flat stage, the angle between the position where a part of the grain first goes to extinction, and where the last portion of the grain reaches extinction was measured for a number of grains in each section. The use of the universal stage was considered for this study, but rejected because the maximum angle will be observed only where the axis of bend-gliding, one of the a-axes, is vertical (Bailey, Bell, and Peng, 1958). Because the position of an a-axis cannot be determined optically, the measurements would still only be an estimate. The results of this study are presented in Appendix C.

The variation in undulatory extinction positions for the nine breccia samples ranges from 2.5° to 19°, and averages approximately 9°. The quartz grains measured included some which exhibit deformation lamellae. The values obtained from the gneisses are quite consistent between samples and do not show a systematic variation with increasing distance from the center of the lake. The angles measured vary from 3.5° to 29° and average approximately 12°. The mean of all samples, but one, is consistently higher than the overall average in the breccias. The one exception has a mean value of 4.8°, and a range of values, from 3.5° to 6°. This sample, 7A2, is among the farthest from the lake.

Undulatory extinction was noted in plagioclase and microcline grains in the breccias. In the former the zones of undulation are roughly perpendicular to the (010) twin plane; and a maximum of 7° displacement was measured.

Structural State of Potash Feldspar

The impact of a meteorite could possibly induce a change in the structural state of the potash feldspar from its original state. O. F. Tuttle (personal communication) has discovered that potash feldspar approaching sanidine in its optical properties occurs in the rocks surrounding the Brent Crater, Ontario. This feldspar occurs in gneissic granites and biotite and/or hornblende gneisses of Precambrian age (Millman et al., 1960), in contrast to the volcanic environment in which Tuttle (1952a) believes that sanidine crystallizes.

It has been demonstrated (Tuttle, 1952b) that heating of natural feldspars reduces their optic axial angle to the extent that the values obtained lie below that for orthoclase and either within or slightly above the range for sanidine. Thus it appears that heating natural feldspars produces a quenchable structural change towards greater degree of disorder, and this process is called sanidinization (Spencer, 1937).

In an attempt to determine whether or not the potash feldspar of the breccia is in a different structural state than the corresponding feldspar of the granitic rocks, two variables of the potash feldspar were measured. As the degree of order decreases towards the higher temperature structural states, the optic axial angle decreases. This is illustrated by the values of $2V_\alpha$ for sanidine (0° to 12°), orthoclase (69° to 72°), and microcline (77° to 84°), as given in Kerr (1959). The optic axial angle of the potash feldspar in ten breccia fragments and six granodiorite gneisses was measured on a five-axis universal stage. The values obtained from the country rock range from $2V_\alpha = 76^\circ$ to 87° (see Appendix D). The majority of 2V values from the breccia samples lie between 72° and 98° but four grains gave significantly different values. These untwinned, non-visibly perthitic, very low birefringent feldspar grains yielded angles between 32° and $38^\circ \pm 5^\circ$ for $2V_\alpha$, and two others, not measured, were estimated to also lie within this region. The orientation of the optic plane could not be determined for these four grains. These comparatively low optic axial angles place these feldspar grains into one of three series determined by Tuttle (1952b). These are: orthoclase-low albite; sanidine-anorthoclase cryptoperthite; high sanidine-high albite. The grains encountered cannot be assigned definitely to any one of these series because their composition is unknown, but all three series involve feldspars believed to have formed at elevated temperatures.

A perthitic, but apparently untwinned potash feldspar from a breccia sample exhibited an optic axial angle of $2V_{\alpha} = 65^{\circ}$. This value places it in the neighborhood of orthoclase.

Another technique for determination of the structural state of potash feldspar is the calculation of its triclinicity. Sanidine and orthoclase are monoclinic, whereas microcline is triclinic. As the degree of order increases in microcline, variations in the unit cell occur from a cell that is barely distinguishable from monoclinic, to one that has the angles $\alpha = 90^{\circ}41'$, $\gamma = 87^{\circ}30'$ (Goldsmith and Laves, 1954). The latter is termed maximum microcline. This degree of departure from monoclinic symmetry is called triclinicity.

The triclinicity of the potash feldspar in the granodiorite gneisses was calculated from five specimens. A similar study was made of the potash feldspar from rock fragments and mineral fragments within five breccia samples. The triclinicity was calculated from the variation in γ^*, which was obtained from the separation of $1\bar{3}1$ and 131 in X-ray powder patterns (Goldsmith and Laves, 1954). No separation will exist in the monoclinic varieties, orthoclase and sanidine.

The triclinicity values for potash feldspar of the gneisses range from 0.93 to $0.96 \pm .01$ and those for the breccias range from 0.92 to $0.96 \pm .01$ (see Appendix D). These figures indicate that the potash feldspar approaches maximum microcline. No difference in the structural state for the feldspars from the two environments is evident from the measurements of their degree of triclinicity.

It was not possible to obtain triclinicity measurements on the four grains which yielded the low optic axial angles, nor on any of the potash feldspars from the samples which contained these four. This was because they are located in microcrystalline matrix breccia pebbles which contain ten per cent or less fragmental material, so that the potash feldspar could not be sufficiently concentrated to yield a suitable X-ray pattern.

CHAPTER VI

DEFORMATION LAMELLAE

During petrographic examination of thin sections of the breccia samples it was noted that some quartz grains which showed the highest interference colors, exhibited sets of parallel lines transecting the grains (see Figures 6-5, -6). Investigation on a five-axis universal stage revealed that these lines are actually the traces of sets of planes within the quartz grains. These planar features were discovered only in the quartz fragments occurring within the breccia, except for one case where they are present in a quartz grain of a rock fragment in a breccia specimen. No such features were seen in the quartz of the country rocks.

Similar planes in quartz have been described in the literature since their apparent discovery by Böhm in 1883, and became known as Böhm lamellae or deformation lamellae by various authors (Christie and Raleigh, 1959). The description of deformation lamellae is varied, and Christie and Raleigh (1959) summarized the various types under five morphologies. They are: (1) those consisting of minute closely-spaced inclusions, (2) those composed partly, but not entirely, of inclusions, (3) those not consisting of inclusions, but narrow zones of a different refractive index from that of the host quartz grain, (4) those composed of planes of brown, sometimes liquid inclusions, also showing a difference in refractive index, (5) those consisting only of brownish granular material.

Under four hundred power magnification the lamellae from the Lac Couture breccias appear to be composed partly of inclusions and partly of zones of unresolvable brownish material. Under eight hundred power parts of the brownish zones can be resolved also into minute inclusions, but other areas are still unresolvable. Some of the inclusions appear to be fluid, but the majority cannot be identified or classified.

The lamellae are visible both in plane-polarized light and under crossed nicols. Although they appear brighter than the host quartz grain under crossed nicols, a distinct difference in birefringence cannot be observed. In plane-polarized light they are also brighter than the enclosing grain and have a lower refractive index than the ordinary ray of the quartz. Most of the authors who have investigated quartz deformation lamellae also report a lower refractive index for the lamellae (Griggs and Bell, 1938; Fairbairn, 1941; Carter, Christie, and Griggs, 1964). Others (Ingerson and Tuttle, 1945) believed that the lamellae had a higher refractive index than the host quartz grain, and a third group recognized a difference in refractive index but were not sure in which direction (Christie and Raleigh, 1959). As a result of studying deformation lamellae in phase-contrast illumination, Christie, Griggs, and Carter (1964) concluded that they are comprised of a region of higher index on one side of a sharp planar discontinuity, and lower on the other side.

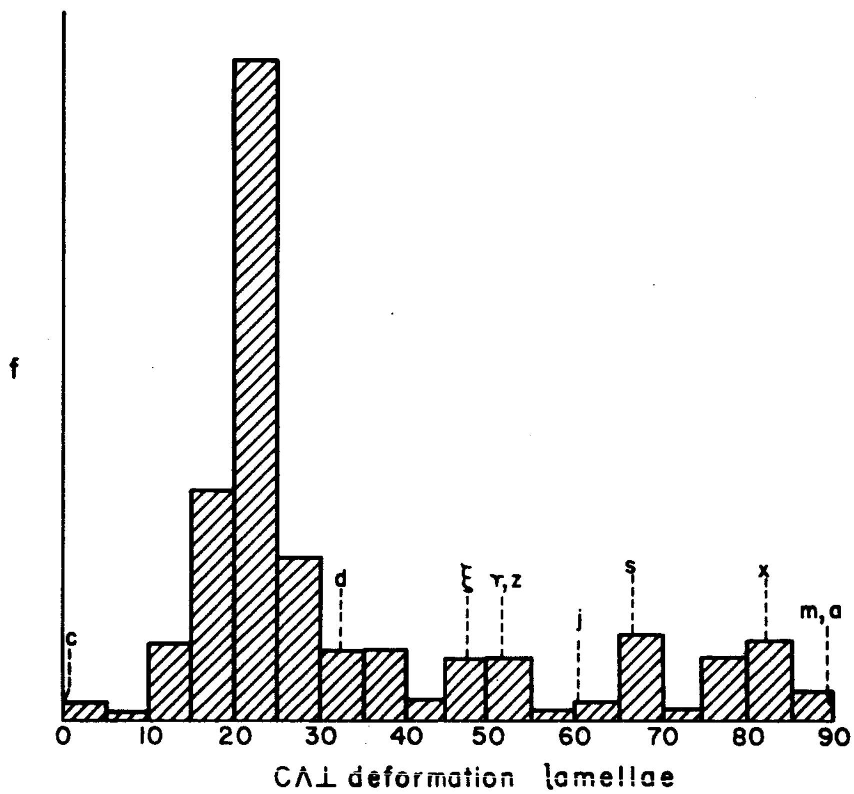
The lamellae investigated in the present study are sharp, narrow, and straight; they extend to the margins of the grains, although some apparently terminate in their interiors. By contrast, Ingerson and Tuttle (1945) described deformation lamellae as not being sharp, straight bands, but as slightly lens-shaped, some or all of which pinch out before reaching the edge of the grain. The Lac Couture lamellae are restricted to a single grain, and do not continue from one grain into the neighboring ones. The quartz grains bearing these lamellae show moderate to strong undulatory extinction, and the lamellae are normal, or almost so, to the undulose bands.

Two, and in places three or more sets of planes are present in a single grain. It is often necessary to rotate the grains about one or more axes on a universal stage in order to bring additional planes into view. Although the entire grain is transected by these planes, most grains with two or more sets show domains where one set or another predominates. For the most part, the planes are straight and parallel to each other, but some curve gently, and a step-like pattern was exhibited by a few planes. No evidence for translational movement was detected along any of these lamellae.

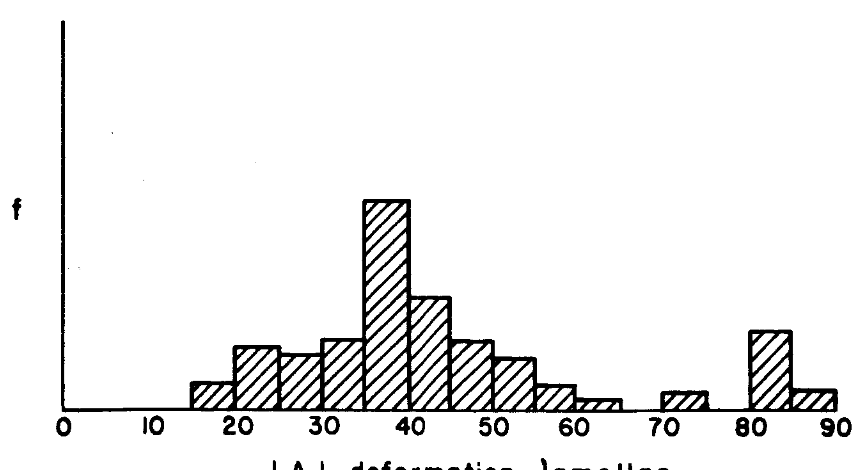
The orientation of the deformation lamellae, with respect to the c-axis of the host quartz grain, was measured on a five-axis universal stage. Five thin sections yielded 117 grains in which lamellae either were visible on a flat stage or could be brought to view by rotation about one or more of the horizontal axes of the universal stage. The angle between the quartz c-axis and the pole to the deformation lamellae was measured for 201 sets of planes, and plotted on a histogram (see Figure 13-1).

Figure 13-1. Relationship between poles to the deformation lamellae and the c-axis of the quartz grains in which they occur (201 measurements). Dotted extensions represent the angle between the normals to cleavage planes in quartz and the c-axis.

Figure 13-2. Interplanar angles for deformation lamellae in quartz (96 measurements).



f
c
d
ξ
r, z
j
s
x
m, a
0
10
20
30
40
50
60
70
80
90
C∧⊥ deformation lamellae



f
0
10
20
30
40
50
60
70
80
90
⊥∧⊥ deformation lamellae

Ingerson and Tuttle (1945) reported that grains showing two or more sets of deformation lamellae are comparatively rare, and Christie and Raleigh (1959) noted that deformation lamellae are only found with one orientation in any grain. Of the 117 grains measured in this study, 63 showed two sets of deformation lamellae, 9 showed three sets, and 1 showed four different sets. From Figure 13-1 it can be seen that the frequency maximum for $c \wedge \perp$ deformation lamellae lies in the 20.1° to 25.0° class. Smaller peaks occur in the 45.1° to 50.0°, 50.1° to 55.0°, 65.1° to 70.0°, and 80.1° to 85.0° classes. It is of interest to note that these points correspond closely to the angles formed by the c-axis and the poles to the ξ, r, z, s, and x cleavages respectively as measured by Bloss and Gibbs (1963). These authors did not find any quartz cleavage whose pole makes an angle of between 20.1° and 25.0° with the c-axis. Bunch and Cohen (1964) likewise make no mention of such a cleavage. Frondel (1962) reported that a rare, but authenticated cleavage form $(10\bar{1}3)$, designated as ω, has been found in a few cases. The pole to this cleavage plane makes an angle of $22^{\circ}56'$ with the c-axis.

Similar orientation studies of deformation lamellae (Fairbairn, 1941; Ingerson and Tuttle, 1945; Christie and Raleigh, 1959; Hansen and Borg, 1962; Carter, Christie, and Griggs, 1964) revealed that they do not form at a constant angle to the c-axis. The $c \wedge \perp$ deformation lamellae angle varies from zero to ninety degrees, as it does in this study, but a maximum usually exists below thirty degrees. Sander (Fairbairn, 1941) recorded a maximum at twenty-two degrees.

The interplanar angles between the sets of deformation lamellae in each grain containing two or more sets, were measured and plotted on a histogram (see Figure 13-2). Most measurements fall within the 35.1° to 40.0° class, with other values spanning the range from 15.1° to 90.0°. There seems to be a distinct tendency for these sets of planes to form at a preferred angle to each other. If the formation of deformation lamellae is controlled by the crystallography of quartz, then the trigonal symmetry of this mineral should be preserved, and three sets of planes would be located about the c-axis. If the angle between $(10\bar{1}3)$ and one of the two faces of the same form, $(\bar{1}103)$ and $(0\bar{1}13)$, is similar to the interplanar angle measured for the deformation lamellae, this would indicate that the latter planes obey the three-fold symmetry. The calculated angle between $(10\bar{1}3)$ and either $(\bar{1}103)$ or $(0\bar{1}13)$ is $39^{\circ}28'17''$.

The characteristics of the deformation lamellae reported in the literature are from quartz grains in deformed rocks (Fairbairn, 1941; Ingerson and Tuttle, 1945; Christie and Raleigh, 1959; Hansen and Borg, 1962) such as quartzites and sandstones from metamorphic terrains, and from experimentally deformed quartz grains (Griggs and Bell, 1938; Carter, Christie, and Griggs, 1964). No record of their occurrence in connection with supposed or verified meteorite craters has been published to the author's knowledge, but M. R. Dence of the Dominion Observatory of Canada has noted these features in rocks from the Deep Bay and West Hawk Lake craters (personal communication). He also notes that Von Engelhardt has discovered these deformation structures from the Ries Kessel, Köfels, and a Swedish crater.

Planes of a similar appearance were observed in a few plagioclase grains in the breccias of the Lac Couture region. These planar features are much less distinct than the corresponding lamellae in quartz, and their composition cannot be resolved even under eight hundred power magnification. They appear to have a higher birefringence and slightly lower refractive index than the host plagioclase grains. The plagioclase grains in which the lamellae were encountered exhibit poorly defined albite twinning. One set of twin lamellae appears unaltered, and contains no deformation lamellae. The other set is dusty brown and usually shows two sets of lamellae. On a flat stage these two sets intersect at an angle of approximately sixty degrees, and are inclined at about thirty degrees to the (010) composition plane of the albite twins.

Dence (personal communication) has noted these features in plagioclase from a supposed meteorite crater in Canada, and reports that Von Engelhardt has found them in the three craters he is investigating.

CHAPTER VII

INVESTIGATIONS FOR COESITE AND STISHOVITE

Coesite, or silica C, is a high pressure polymorph of SiO_2, with monoclinic symmetry. It was first synthesized by Coes (1953) at 500°-800°C and 35,000 atmospheres pressure. This polymorph had not been found in nature prior to its laboratory synthesis, but X-ray examination of the Coconino Sandstone from Meteor Crater, Arizona, revealed its presence in this highly shocked formation (Chao, Shoemaker, and Madsen, 1960). Its existence has now also been confirmed in a suevite from the Ries Kessel crater, Bavaria (Pecora, 1960). Coesite has not been found in any natural environment other than those believed to have been created by a meteorite impact.

Stishovite is another high pressure polymorph of silica, with tetragonal symmetry. It was first synthesized at 160,000 atmospheres and greater than 1,200°C (Stishov and Popova, 1961). Up to the present time, the only known natural occurrence of this mineral is in the Coconino Sandstone from Meteor Crater, Arizona (Chao et al., 1962).

Coesite and stishovite could not be seen in the thin sections of the breccia samples from Lac Couture. To determine if they are present in submicroscopic grains, samples of the breccia were digested in hydrofluoric acid, and the residue X-rayed. For this study eighteen hand specimen size breccia samples were crushed in three stages, to approximately -200 mesh size. In addition, for control purposes, a sample of suevite from the Ries Kessel known to contain coesite and a granodiorite sample assumed to be barren of coesite were crushed in the same manner.

Ten grams of seventeen breccia samples and the two control samples were further crushed in a mullite mortar and pestle until no gritty feel remained. Forty grams of the remaining sample was prepared in the same way.

The digestion and concentration procedure used is based on the fact that stishovite is not attacked by either concentrated or dilute hydrofluoric acid, and coesite is slowly attacked by hydrofluoric acid at room temperature, but is more resistant than quartz (Fahey, 1964).

Digestion of each sample was carried out in 180 ml. of five per cent HF at room temperature, in a 400 ml. teflon crucible. The volume of acid used was based on the amount required to dissolve all the silica, assuming each sample to contain approximately seventy per cent SiO_2. The digestion process was allowed to proceed for fifteen to twenty-four hours, after which the acid was decanted, leaving any undissolved material in the crucible. The residue was treated with an acid solution (20 ml. of concentrated HCl, plus 10 ml. of concentrated HNO_3, plus 20 ml. of distilled water) in order to dissolve any uni- and di-valent cation silicon-fluorides which might have formed. This mixture was left at room temperature for another fifteen to twenty-four hours, after which it was filtered and the residue washed with distilled water, and allowed to dry at room temperature. The above processes were repeated (usually four times) until the original sample was reduced to less than one half gram. The total time for a complete run varied between two and three weeks.

The final residue was X-rayed on a diffraction unit, and the pattern was compared with known patterns for coesite and stishovite which were obtained from Dr. J, Fahey of the U.S.G.S.

Coesite was found by this method in the suevite sample from Ries Kessel, but stishovite was not recorded in this rock. None of the ten gram breccia samples, nor the forty gram sample, nor the granodiorite showed any indication of the presence of either coesite or stishovite. The concentration procedure eliminated all minerals from the sample except for quartz, and small amounts of K_2SiF_6 and $16AlF(OH)_2$ or $16AlF_2(OH)$ produced during the breakdown. These latter compounds were also removed by an additional acid treatment.

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Summary

The area investigated surrounds Lac Couture in the northern part of the Province of Quebec, Canada. The circularity of this lake prompted this investigation to determine whether it perhaps is a crater formed by the impact of a meteorite or to suggest some other mode of origin.

The map region is underlain by gneissic rocks of granitic to granodioritic composition. Modal analyses indicate that the latter is the most common. Mineralogically these rocks are composed of quartz and varying amounts of oligoclase, microcline microperthite, biotite, epidote, chlorite, and muscovite, in an allotriomorphic-granular texture. A gneissic banding is poorly developed in most of these rocks, and a foliation is found in some outcrops.

Variations from this overall picture, in mineralogy or texture, produce local changes in the rock type. The appearance of abundant hornblende, pyroxene, or epidote, and a trend towards more albitic plagioclase distinguish some of these rocks from the surrounding country rock. Others are distinctive because of their augen structure.

Two sets of diabase dykes cut the gneisses. Modal analyses were made on several of these and also on a number of the varieties within the country rock.

Boulders and pebbles of breccia occur in a narrow fan on the western side of Lac Couture. The angular mineral fragments and granitic rock fragments in these range from less than 0.01mm. in diameter to pebbles up to 1 foot or larger. The fragmental material comprises ten to ninety per cent of the breccias, the remainder being a clastic, cryptocrystalline, or microcrystalline matrix of quartz and feldspar. Oval and irregularly shaped vesicles and amygdules filled with a cryptocrystalline material occur in samples where the crystalline matrix is coarsest and the proportion of fragments is at a minimum. Banding, created by differences of grain size, and apparent flow textures are also common in the crystalline matrix. Deformation features exhibited by the mineral fragments include fracturing, undulatory extinction, replacement of plagioclase by the matrix, and deformation lamellae.

The deformation lamellae in quartz are sharp planar features composed partly of inclusions. They have a lower refractive index than the ordinary ray of the host quartz grains. Sets of these lamellae are inclined at all angles to the c-axis, but most are at a high angle to this crystallographic reference axis. Most of the interplanar angles between sets of lamellae are close to forty degrees.

The gneissic banding and foliation of the country rocks trend approximately north-northwest and dip steeply to both the east and west. In a few outcrops these planar structures strike east-northeast and dip gently to the south.

The majority of the lineations in the country rocks plunge to the southeast at approximately sixty degrees to the horizontal. The rest possess the same azimuth but plunge to the northwest.

Combining these features with an aerial photograph interpretation of the regional structure reveals a series of concentric antiform and synform folds trending and plunging to the southeast.

Sheeting joints in the rocks around Lac Couture are subhorizontal. At a distance of approximately two miles from the circumference of the lake the dip is slightly higher and horizontal joints are virtually absent.

The joint pattern in the granitic rocks and diabases was compared for the four quadrants in which the field observations were made, and also as a function of distance from Lac Couture. Steeply dipping joints trend in all directions, but three pronounced sets do exist in the regional scheme. The joints near the crater do not possess the same attitudes as those located more than three miles from the crater, but the joint pattern does not differ appreciably from one quadrant to another.

Undulatory extinction in quartz is very evident in the country rocks and breccias. The variation in extinction position in a particular quartz grain in the breccias ranges from 2.5° to 19° and averages approximately 9°. In the granitic rocks the angles vary from 3.5° to 29° and average approximately 12°.

Optic axial angles of the potash feldspar range between 76° and 87° for $2V_{\alpha}$ in the granitic rocks. In the breccias most of the values lie between 72^{o} and 98^{o}, but four grains yielded values between 32^{o} and 38^{o}, and another was measured as 65^{o}.

The triclinicity of potash feldspar in five breccia samples ranges from 0.92 to 0.96, and in five samples of gneiss ranges from 0.93 to 0.96.

An X-ray investigation of the breccias for coesite and stishovite did not reveal the presence of these high pressure forms of silica.

Conclusions

The region around Lac Couture is underlain, for the most part, by granitic and granodioritic gneisses of the almandine-amphibolite facies of regional metamorphism (Turner and Verhoogen, 1960). The presence of oligoclase, microcline, epidote, biotite, and minor hornblende in rocks possessing a gneissosity or foliation, is the basis for this classification. Retrograde metamorphism has converted part or all of the biotite to chlorite and muscovite.

The variations in mineralogy within the gneisses reflect localized differences in metamorphic grade. Samples 4A4, 2D5, 4D8, and 5D3 belong to the greenschist facies of regional metamorphism, as determined by their albitic plagioclase, chlorite, epidote, and minor tremolite-actinolite content. Samples 4A7, B7, 4D14, and 5D5 belong to the almandine-amphibolite facies, but their abundant hornblende and pyroxene indicates that they are of a slightly higher grade of metamorphism than most of the gneisses. The albitic plagioclase of sample

4A7 appears contradictory to this, but the zones of bleached amphibole and the laths of chlorite within the hornblende are probably the products of later hydrothermal activity, of which the albite is presumed to be a product.

Other evidences of a period of later hydrothermal activity are furnished by the abundant epidote veins cutting the gneisses and by the late stage minerals of the diabases, such as quartz, apatite, and clay minerals.

The breccia may be of the type known as an "impactite", which is characterized by microbreccias in chaotic arrangements, often held in a glassy or devitrified glassy matrix (Short, 1964). The cryptocrystalline and microcrystalline matrix of some of the breccia fragments, plus the presence of vesicles, amygdules, and flow structures are indications that the matrix was fluid at some time. The crystalline matrix could be the devitrification product of a glass. The banding created by differences in grain size is due to differences in the degree of devitrification. This banding was probably parallel to the crater floor when the breccia was emplaced, and lithostatic pressure from the upper layers of breccia and later sediments instigated the devitrification. A second age of fluid filled the amygdules, but the degree of devitrification from this presumed glass has not proceeded to the same extent as the matrix.

The origin of deformation lamellae in quartz is still in debate, but a general agreement persists that they are a result of structural deformation. Their complete absence in the gneisses indicates that the deformation accompanying regional metamorphism was not their cause. The orientation of these planes within the quartz is also a matter still open to discussion. The apparent agreement with trigonal symmetry exhibited by the lamellae in the Lac Couture quartz grains suggests that they are at least partially controlled by the crystallography of the quartz. This is further supported by their minor coincidence with the known cleavages of quartz, which definitely occur along rational planes of weakness. On the other hand, the fact that they do form at all angles to the c-axis seems to indicate that their orientation is also partially influenced by some other factor, perhaps a directed stress.

Until the breccia is actually found in place the source of these erratics cannot be ascertained. However, all indications point to Lac Couture as this source. Glaciation has proceeded from east to west, and the erratics of breccia are found only on the western side of Lac Couture. The size and frequency of the erratics decrease westward from the shores of Lac Couture. The mineralogy and texture of the rock fragments of the breccias are similar to those of the gneisses around Lac Couture. It is, therefore, reasonable to believe that the glacial erratics of breccia were scoured from the depths of Lac Couture during glaciation.

If the rock fragments are from the gneisses which originally occupied the site of Lac Couture, this could explain why the triclincity of the potash feldspar is the same in the breccias and the gneisses: either the energy involved in formation of the breccias was insufficient to disorder the feldspar structure, or that the disordered structure coincidentally came to equilibrium in the same state as the potash feldspar of the country rock. It seems that in at least a few instances the structural state has become partially disordered. The four grains whose measured optic axial angles lie between 32° and 38° are due, most likely, to a process of sanidinization. This process has occurred under the influence of high temperatures and perhaps high pressures.

The attempt to equilibrate degree of undulatory extinction of quartz grains with distance from the crater did not yield results of significance. The undulatory extinction was probably produced during regional metamorphism. The undulatory extinction is less strong in the breccias than in the gneisses. Undulatory extinction exists in deformed rocks which have not been recrystallized (Bailey, Bell, and Peng, 1958). The quartz of the breccias has probably undergone some slight recrystallization, and thus its undulatory extinction has been weakened.

The Lac Couture crater belongs to a group of features known as either cryptovolcanic craters or astroblemes (meteorite craters). These craters are roughly circular basins believed to be produced by a sudden explosive release of material from within the earth, or by the impact of a meteorite. Both types possess several similar criteria for their identification and they are thus difficult to distinguish from one another. They generally have an elevated rim which has been eroded to some extent. Impactites are considered by Short (1964) to be definitive features of meteorite craters. In support of this they have been found in several craters believed to be of meteoritic origin, including Meteor Crater, Arizona (Chao et al., 1960), and Deep Bay, Saskatchewan (Innes, Pearson, and Geuer, 1964). Snyder and Gerdemann (1965), however, found similar breccias in several structures which they believed were created by explosive volcanic activity.

Shatter cones, also attributed to an impact origin by Short, are found in these cryptovolcanic structures. The presence of coesite and stishovite in the shocked rocks has been suggested as a reliable criterion for identifying meteorite craters, but coesite has been produced in a one million-pound chemical explosion crater (Short, 1964).

What topographic expressions of this crater still exist? The distinct circularity of Lac Couture in a region where the lakes are elongate and follow the glaciated channels, indicates that this lake has not been created by glaciation. Lac Couture has been superimposed upon the regional structure as seen by the fact that the folds and photo-lineations are truncated by the lake, and they do not bend around it. Thus the crater is later than regional metamorphism.

The differences, slight though they may be, between the attitudes of the sheeting and other joints near the crater and those at some distance from the lake, cannot be construed as indicating the remnants of a crater rim. They do, however, further strengthen the argument that the area within approximately two miles of the shores of Lac Couture is different from the surrounding area.

The apparent absence of coesite and stishovite from the breccias in no way weakens the hypothesis that these rocks are impactites. These minerals have been recognized from only six meteorite craters, although several other craters in which they are apparently absent are believed to be meteoritic in origin. These high pressure polymorphs may actually be present in the Lac Couture breccias, but they could not be detected because of the difficulty in concentrating them by the technique employed. Short (1964) states that chances are better for finding coesite and stishovite in the rubble tossed out by the cratering process. The material examined in this study was probably removed by scouring of the lake by glaciation and not by the explosion. Coesite and stishovite, being high pressure forms, are quite unstable under surface conditions; even if formed by an impact or explosion, they could have reverted over geologic time to the lower pressure, more stable phases (Short, 1964).

Lac Couture cannot, from the information gathered in this study, be definitely classified as either a meteorite crater, or as a cryptovolcanic crater. In fact the apparent absence of an elevated rim, shatter cones, and coesite and stishovite make it difficult to assign it to the broad range of features encompassed by cryptovolcanic craters and astroblemes.

However, the impactite type of breccia and the deformation lamellae, both found in meteorite craters (Dence, personal communication) strengthen the case for this mode of formation for Lac Couture. On the other hand, the two ages of glass are more readily explained as the products of igneous activity accompanying cryptovolcanic activity.

Another hypothesis which may be invoked to explain this circular lake is that Lac Couture is the eroded remnant of a volcano. The only volcanic rocks in this area, however, is the belt of gneisses described by Stevenson (1965).

Future studies concerned with the origin of Lac Couture should involve sampling the crater floor by drilling, and determining the lake's profile by soundings.

BIBLIOGRAPHY

Aubert de la Rue, E., 1948, Geological Survey through the Ungava Peninsula, Arctic, vol. 1, pp. 135-136.

Bailey, S. W., Bell, R. A., and Peng, C. J., 1958, Plastic Deformation of Quartz in Nature, Geol. Soc. America Bull., vol. 69, pp. 1443-1466.

Banfield, A. W. F., 1964, The Unbelievable Land, Edited by I. N. Smith, The Queen's Printer, Canada, pp. 25-26.

Beals, C. S., Innes, M. J. S., and Rottenberg, J. A., 1960a, The Search for Fossil Meteorite Craters, Contr. Dom. Obs., vol. 4, no. 4.

_____, 1960b, Fossil Meteorite Craters, Contr. Dom. Obs., vol. 5, no. 20.

Beals, C. S., Dence, M. R., and Cohen, A. J., 1964, Evidence Suggesting a Meteorite Impact Origin for Lac Couture, Quebec, Astron. Jour., vol. 69, p. 134.

Bell, R., 1879, Report on an Exploration of the East Coast of Hudson Bay, Geol. Surv. Canada Rept. of Progress 1877-1878.

Billings, M. P., 1954, Structural Geology, 2nd ed., Prentice-Hall Inc.

Bloss, F. D., and Gibbs, G. V., 1963, Cleavage in Quartz, Am. Mineralogist, vol. 48, pp. 821-838.

Bunch, T. E., and Cohen, A. J., 1964, Shock Deformation of Quartz from Two Meteorite Craters, Geol. Soc. America Bull., vol. 75, pp. 1263-1266.

Carter, N. L., Christie, J. M., and Griggs, D. T., 1964, Experimental Deformation and Recrystallization of Quartz, Jour. Geol., vol. 72, pp. 687-733.

Chao, E. C. T., Shoemaker, E. M. and Madsen, B. M., 1960, The First Natural Occurrence of Coesite from Meteor Crater, Arizona, Science, vol. 132, pp. 220-222.

Chao, E. C. T., Fahey, J. J., Littler, J., and Milton, D. J., 1962, Stishovite, SiO_2 a Very High Pressure New Mineral from Meteor Crater, Arizona, Jour. Geophys. Res., vol. 67, pp. 419-421.

Chayes, F., 1952, Notes on the Staining of Potash Feldspar with Sodium Cobaltinitrite in Thin Section, Am. Mineralogist, vol. 37, pp. 337-340.

Christie, J. M., and Raleigh, C. B., 1959, The Origin of Deformation Lamellae in Quartz, Am. Jour. Science, vol. 257, pp. 385-407.

Christie, J. M., Griggs, D. T., and Carter, N. L., 1964, Experimental Evidence of Basal Slip in Quartz, Jour. Geol., vol. 72, pp. 734-756.

Coes, L., Jr., 1953, A New Dense Crystalline Silica, Science, vol. 118, pp. 131-132.

Deer, W. A., Howie, R. A., and Zussman, J., 1963, Rock-Forming Minerals, vol. 4, John Wiley and Sons Inc., pp. 130-131.

Emmons, R. C., 1943, The Universal Stage, Geol. Soc. America Mem. no. 8, pp. 115-133.

Fahey, J. J., 1964, Recovery of Coesite and Stishovite from Coconino Sandstone of Meteor Crater, Arizona, Am. Mineralogist, vol. 49, pp. 1643-1647.

Fairbairn, H. W., 1941, Deformation Lamellae in Quartz from the Ajibik Formation, Michigan, Geol. Soc. America Bull., vol. 52, pp. 1265-1277.

Frondel, C., 1962, Dana's System of Mineralogy, vol. III, 7th ed., John Wiley and Sons Inc.

Gold, D. P., 1965, Study of Structural and Mineralogical Significance of Meteorite Impact Sites, Including Mineral Paragenesis, High Pressure Polymorphs, Microfractures, and Quartz Lamellae, 2nd Ann. Rept. to NASA.

Goldsmith, J. R., and Laves, F., 1954, The Microcline-Sanidine Stability Relations, Geochim. et Cosmochim. Acta, vol. 5, pp. 1-19.

Griggs, D. T. and Bell, J. F., 1938, Experiments Bearing on the Orientation of Quartz in Deformed Rocks, Geol. Soc. America Bull., vol. 49, pp. 1723-1746.

Hansen, E., and Borg, I., 1962, The Dynamic Significance of Deformation Lamellae in Quartz of a Calcite-Cemented Sandstone, Am. Jour. Science, vol. 260, pp. 321-336.

Ingerson, E., and Tuttle, O. F., 1945, Relations of Lamellae and Crystallography of Quartz and Fabric Directions in Deformed Rocks, Am. Geophys. Union Trans. 1944, pp. 95-105.

Innes, M. J. S., Pearson, W. J., and Geuer, J. W., 1964, The Deep Bay Crater, Pub. Dom. Obs., vol. XXXI, no. 2.

Kerr, P. F., 1959, Optical Mineralogy, 3rd ed., McGraw-Hill Book Co. Inc.

Kretz, R., 1960, Geological Observations in Northern New Quebec, Geol. Surv. Canada Paper 60-12.

Krumbein, W. C., 1941, Measurement and Geological Significance of Shape and Roundness of Sedimentary Particles, Jour. Sed. Petrology, vol. 11, pp. 64-72.

Laniz, R. V., Stevens, R. E., and Norman, M. B., 1964, Staining of Plagioclase Feldspar and Other Minerals with F. D. and C. Red, No. 2, U. S. Geol. Surv. Prof. Paper 501B, pp. B152-B153.

Lloyd, T., 1964, The Unbelievable Land, Edited by I. N. Smith, The Queen's Printer, Canada, p. 1.

Low, A. P., 1898, Exploration of Part of the South Shore of Hudson Strait and of Ungava Bay, Geol. Surv. Canada Ann. Rept., vol. 11.

_____, 1900, Report on an Exploration of the East Coast of Hudson Bay from Cape Wolstenholme to the South End of James Bay, Geol. Surv. Canada Ann. Rept., vol. 13.

Meen, V. B., 1957, Chubb Crater-A Meteor Crater, Jour. Roy. Astron. Soc. Canada, vol. 51, pp. 137-154.

Millman, P. M., Liberty, B. A., Clark, J. F., Willmore, P. L., and Innes, M. J. S., 1960, The Brent Crater, Pub. Dom. Obs., vol. XXIV, no. 1.

National Topographic Series, Canada, 1958a, Payne River, 34 N.E.

_____, 1958b, Povungnituk River, 35 S.E.

Pecora, W. T., 1960, Coesite Craters and Space Geology, Geotimes, vol. 5, pp. 16-19.

Rice, H. M. A., and Harker, P., 1961, Guide for the Preparation of Geological Maps and Reports, Geol. Surv. Canada.

Rosenblum, S., 1956, Improved Techniques for Staining Potash Feldspars, Am. Mineralogist, vol. 41, pp. 662-664.

Short, N., 1964, Nuclear Explosion Craters, Astroblemes, and Cryptoexplosion Structures, University of Calif. Radiation Laboratory Pub., UCRL-7787.

Snyder, F. G., and Gerdemann, P. E., 1965, Explosive Igneous Activity along an Illinois-Missouri-Kansas Axis, Am. Jour. Science, vol. 263, pp. 465-493.

Spencer, E., 1937, The Potash-Soda Feldspars. I. Thermal Stability, Min. Mag., vol. 24, pp. 453-494.

Stevenson, I. M., 1963, Leaf River Map-Area, New Quebec, Geol. Surv. Canada Paper 62-24.

_____, 1965, Leaf River Map-Area, Quebec and District of Keewatin, Geol. Surv. Canada Paper 64-28.

Stishov, S. M., and Popova, S. V., 1961, New Dense Polymorphic Modification of Silica, Geokhimiya, vol. 10, pp. 837-839.

Stockwell, C. H., 1964, Age Determinations and Geological Studies, Geol. Surv. Canada Paper 64-17, part II.

Tanner, J. G., and McConnell, R. K., 1964, Gravity Map Series Dom. Obs., no. 5, Cape Smith-Povungnituk.

Turner, F. J., and Verhoogen, J., 1960, Igneous and Metamorphic Petrology, 2nd ed., McGraw-Hill Book Co. Inc.

Turner, F. J., and Weiss, L. E., 1963, Structural Analysis of Metamorphic Tectonites, McGraw-Hill Book Co. Inc.

Tuttle, O. F., 1952a, Origins of the Contrasting Mineralogy of Extrusive and Plutonic Salic Rocks, Jour. Geol., vol. 60, p. 107.

_____, 1952b, Optical Studies on Alkali Feldspars, Am. Jour. Science, Bowen vol., pp. 553-567.

APPENDIX A

MODAL ANALYSES

Modal analyses were compiled by point counting four hundred points per thin section. As an aid in identification of plagioclase, potash feldspar, and quartz, half of each thin section was stained (Chayes, 1952; Rosenblum, 1956; Laniz, Stevens, and Normal, 1964).

Granitic Rocks

Sample	Quartz	Plagioclase	Microcline	Biotite and Chlorite	Epidote	Muscovite	Others
10	33.0%	48.0%	15.3%	2.3%	0.0%	1.5%	0.0%
12	33.3	38.8	20.3	6.3	0.0	1.3	0.3
26	22.8	64.3	0.3	10.5	0.8	1.0	0.5
2A1	21.3	58.8	11.5	6.5	1.3	0.0	0.8
5A3	34.5	40.3	10.5	11.0	0.8	3.0	0.0
7A1	34.0	56.5	3.8	3.5	0.8	1.5	0.0
7A2	30.3	50.5	16.8	1.8	0.0	0.8	0.0
2B2	27.3	24.3	47.5	0.5	0.0	0.5	0.0
6B7	26.3	30.3	40.8	1.5	0.5	0.8	0.0

Granitic Rock Variants

Sample	Plagioclase	Amphibole	Pyroxene	Biotite and Chlorite	Microcline	Quartz	Epidote	Others
4A7	15.8%	69.3%	- %	8.5%	- %	- %	4.8%	1.8%
4D14	5.5	45.0	36.5	-	-	-	5.5	7.5
B7	42.3	32.0	2.3	9.3	4.3	9.8	-	0.3
[illegible]	[illegible]	-	-	11.0	[illegible]	[illegible]	[illegible]	2.3

APPENDIX A (Continued)

Diabases

Sample	Plagioclase	Amphibole	Pyroxene	Biotite	Opaque	Quartz	Epidote	Others
B12-2b	57.5%	7.5%	31.8%	- %	2.3%	0.3%	- %	0.8%
B16b	37.5	3.3	53.3	-	6.0	0.0	-	0.0
7B2a	42.0	11.0	37.8	3.5	5.3	0.5	-	0.0
5D1	40.3	4.3	47.0	-	6.5	0.0	2.0	0.0

APPENDIX B

PLAGIOCLASE COMPOSITIONS

The composition of the plagioclase feldspar was determined by the Rittmann zone method (Emmons, 1943) and Smith's method (Deer, Howie, and Zussman, 1963). The former technique utilizes the extinction angles of the albite twins, and the latter is based on the measurement of the α refractive index. The α refractive index of the grains measured was determined in oils, under sodium light, and corrected to twenty-six degrees Centigrade.

Granitic Rocks

Sample	N_α	Composition: Smith	Composition: Rittmann Zone
10	$1.537\pm.001$	$An_{16\pm2}$	An_{18}
12	-	-	An_{23}
14	$1.538\pm.001$	$An_{18\pm2}$	-
26	$1.538\pm.001$	$An_{18\pm2}$	An_{23}
2A1	$1.537\pm.001$	$An_{16\pm2}$	An_{17}
5A3	$1.541\pm.001$	$An_{23\pm2}$	An_{25}
7A1	$1.538\pm.001$	$An_{18\pm2}$	-
7A2	$1.536\pm.001$	$An_{14\pm2}$	An_{24}
2B2	$1.536\pm.001$	$An_{15\pm2}$	-
3B4	-	-	An_{23}
6B7	$1.537\pm.001$	$An_{16\pm2}$	An_{15}

Country Rock Variants

Sample	N_α	Composition: Smith
4A4	$1.529\pm.001$	$An_{1\pm2}$
4A7	$1.533\pm.001$	$An_{9\pm2}$
B7	$1.541\mp.001$	$An_{23\pm2}$
2D5	$1.529\pm.001$	$An_{1\pm2}$
4D8	$1.533\pm.001$	$An_{8\pm2}$
4D14	$1.545\pm.001$	$An_{32\pm2}$
5D3	$1.528\pm.001$	$An_{1\pm2}$
5D5	$1.538\pm.001$	$An_{18\pm2}$

APPENDIX C

UNDULATORY EXTINCTION IN QUARTZ

Granitic Rocks

Sample	Distance from center of Lac Couture	Mean Angle
10	4 miles	14.4°
12	3	11.6
26	3	11.7
2A1	6	11.2
5A3	3½	11.9
7A1	8	11.6
7A2	7	4.8
2B2	4½	19.5
3B4	5	15.6
6B7	3	12.2
	Overall mean 12.3°	

Breccia

Sample	Mean Angle
1	6.4°
1a	4.5
4	8.1
3A9	8.5
6A4	10.6
3B7	14.8
3B7a	5.3
F	9.9
F3	10.9
	Overall mean 8.9°

APPENDIX D

STRUCTURAL STATE OF POTASH FELDSPAR

An attempt to determine the structural state of the potash feldspars in the granitic rocks and in the breccias was made by measuring their optic axial angles and calculating their triclinicity. The former measurements were made on a five-axis universal stage, and the latter was determined from the separation of the (131) and ($1\bar{3}1$) peaks on an X-ray diffraction pattern (Goldsmith and Laves, 1954).

Granitic Rocks

Sample	Distance from Center of Lac Couture	Mean $2V_\alpha$	$d_{1\bar{3}1}-d_{131}$	Triclinicity
10	4 miles	83.8°	0.0765	0.95±.01
2A1	6	81.5	0.0764	0.95±.01
7A2	7	-	0.0741	0.93±.01
2B2	4½	81.5	0.0770	0.96±.01
6B7	3	84.1	0.0770	0.96±.01
5A3	3½	81.0	-	-
12	3	80.9	-	-

Breccias

Sample	Mean $2V_\alpha$	$d_{1\bar{3}1}-d_{131}$	Triclinicity
3A4	- °	0.0769	0.96±.01
3A9	80.5	0.0766	0.95±.01
6A4	-	0.0737	0.92±.01
B11	-	0.0756	0.94±.01
3B7	80.6	0.0766	0.96±.01
3B7a	82.2	-	-
1	82.2	-	-
F	80.8	-	-
F1	84.6	-	-
F2	78.7	-	-
F3	92.3	-	-
Island B	79.5	-	-

APPENDIX D (Continued)

Optic Axial Angles of Potash Feldspar Other Than Microcline

Sample	$2V_\alpha$
1	$65^\circ \pm 2^\circ$
LCP8	$38^\circ \pm 5$
	$37^\circ \pm 5$
LCP11	$35^\circ \pm 5$
	$32^\circ \pm 5$